STELLINGEN

De ammoniakemissie uit Nederlandse melkveestallen wordt in belangrijke mate overschat, hetgeen betekent dat zowel de betreffende uitgangspunten in de nationale emissiemodellen als de emissiefactor voor ligboxenstallen herzien moeten worden (dit proefschrift).

Een nauwkeurig vastgestelde pH van de emitterende oppervlaktelaag is essentieel voor een correcte berekening van de ammoniakemissie uit melkveestallen (dit proefschrift).

Veehouders zijn zeer goed in staat om de ammoniakemissie uit stallen via managementmaatregelen, dus zonder dwingende regelgeving, terug te dringen de beschikking, mits ze de beschikking krijgen over een geijkte ammoniakmeter.

Het gebruik van toevoegmiddelen aan de mest of het veevoer op duurzame melkveebedrijven heeft op het stikstofverlies niet meer dan een placebo-effect (Dubbeldam, 2000).
Dubbeldam, R. (Ed.), 2000. De sporen van twee milieucoöperaties. NLTO, Drachten, 44 pp.

In de discussie rond het sluiten van mineralenkringlopen in het milieu wordt ten onrechte de mens als bron niet meegenomen (Isermann & Isermann, 1999).
Isermann, K. and R. Isermann, 1999. Healthy eating habits of the population of the so-called "developed" countries ensure an almost reasonably sufficient reduction of emissions. Paper presented at the international conference on biogenic emissions of greenhouse gases caused by arable and animal agriculture, 13-15 October 1999, Stuttgart, 2 pp.

Met het oog op de voedselveiligheid voor toekomstige generaties dient de accumulatie van zink en koper in de bodem met voorrang te worden teruggedrongen (Windisch, 2000).
Windisch, W., 2000. Pollutants in animal manure: factors of emission and strategies for reduction. Paper presented at the international workshop on Sustainable Animal Production, 28-29 October 2000, Hannover, 4 pp.

Het in enige mate stressen van de bodem en de mens heeft een zelfde gevolg, namelijk een toename van de productiviteit (vrij naar: Whitmore, 2000).
Whitmore, A.P., 2000. Impact of livestock on soil. Paper presented at the international workshop on Sustainable Animal Production, 28-29 October 2000, Hannover, 4 pp.

Stellingen behorend bij het proefschrift
Modelling of ammonia emissions from dairy cow houses

Wageningen, 18 december 2000

Gert-Jan Monteny

Modelling of ammonia emissions from dairy cow houses

Gert-Jan Monteny

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Modelling of ammonia emissions from dairy cow houses

Gert-Jan Monteny

Proefschrift

Ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit
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in het openbaar te verdedigen
op maandag 18 december 2000
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s middags om half twee in de Aula.

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Abstract

Monteny, G.J. (2000). Modelling of ammonia emissions from dairy cow houses. PhD thesis, Wageningen University, Wageningen, the Netherlands (156 pp., with summaries in English and Dutch).

Keywords: cubicle houses, environmental pollution, acidification, emission reduction, validation, simulations

Dairy cow husbandry contributes to environmental acidification through the emission of ammonia. In-depth knowledge on the processes and variable factors that play a role in the emission of ammonia from dairy cow houses benefits the production of emission data, the development of low emission housing systems, and evaluation of emission levels in a farming system approach. A mechanistic simulation model for the ammonia emission from dairy cow houses was developed to facilitate this.

An ammonia production model, with separate modules for the emission from the slurry pit and the slatted floor, was built and validated against measured data on the ammonia emission. Model improvements followed from this validation and were addressed in experiments on the development of the pH of urine deposited on floors and slurry, and on quantification of air exchange rates through slatted floors. The pH experiments revealed that the urine pH, after the urine was deposited on the floor or the slurry, increased to greater values than originally assumed. Furthermore, the air exchange through the openings of slatted floors was quantified, which made it possible to separately simulate the ammonia emission from the pit and from the floor. These unique theories were used to build a real ammonia emission model, with ammonia mass balances for the slurry pit and the air above the floor. The emission model was successfully validated against emission measurements conducted in a mechanically ventilated and a naturally ventilated cow house. The potential of the model to simulate emission levels (both in terms of emission factors and emission fractions), and measures that reduce ammonia emissions was illustrated using data obtained from an experiment with various dairy cow diets.

Voor pa, ma, Elma, Nick en Mike

Contents

Account:
Parts of this thesis have been or will be published in international scientific journals. Chapter 2 was published as Netherlands Journal of Agricultural Science 46 (1998): 225-247. Chapter 3 was published as Transactions of the ASAE 41 (1): 193-201. Chapters 4, 5 and 6 have been submitted to various journals.

Minor typographical changes were made. The lay-out of all chapters was standardised. Furthermore, chapter numbers were included in the numbering of the tables and figures. The original language of submission was not changed, so differences in UK English and USA English occur (e.g. faeces and feces). References should be made to the original articles.

1

General introduction

1 Introduction

There is general consensus that the emission of ammonia (NH_3) from anthropogenic sources like agriculture has to be reduced to protect natural ecosystems. The goals of environmental protection policies for NH_3 emission and nitrogen (N) deposition are to minimise eutrophication and acidification, and to maintain biodiversity in the future (Erisman *et al.*, 1998). Within global agriculture, cattle husbandry is the major single source of anthropogenic NH_3 emission (Bouwman *et al.*, 1997). Its NH_3 originates mainly from application of excreta on the field (grassland, arable land), from housing systems, and to a lesser extent from outdoor storages, grazing and crop residues. On a farm scale, around 25% of the N excreted in the cattle urine and faeces, which is 20% of the total N input, is lost as NH_3 (Aarts *et al.*, 1992; Aarts, 2000). Measures to reduce NH_3 emission from land application of excreta are used increasingly in dairy farming, either to prevent the loss of fertiliser value or to comply with NH_3 abatement legislation (e.g. in the Netherlands). However, future environmental constraints require the development of dairy farming systems with minimal losses of nutrients (N, phosphorus, potassium) to the environment. All stages in the nutrient cycle on dairy farms have to be taken into account in an integrated way to achieve this.

The cow house plays a central role in dairy farming systems. It is the place where, at least during a major part of the year, nutrient inputs through silage and concentrates are converted to products that leave the farm for human consumption (milk, meat) or that are re-used within the system through the excreta (further referred to as slurry). The vast majority of dairy cattle is housed in naturally ventilated buildings. The two most common types of cattle houses are free stalls (referred to as cubicle houses), with separate areas for resting and feeding, and tie stalls, where both areas are combined. Cubicle houses typically have slatted or solid floors with underfloor slurry storage, whereas the slurry from tie stalls is usually transported to an outside storage. In both cases, the NH_3 produced and emitted not only depends on the diet and details in the design of the house, but also on the outdoor and indoor climate, and the management routine on the farm (e.g. the grazing strategy).

Establishing NH_3 emission data for use in the Dutch NH_3 emission abatement legislation, referred to as emission factors, requires complex and costly measuring techniques, especially for naturally ventilated animal houses. As a consequence, the current emission factors for traditional and newly developed dairy cow housing systems are based on measurements conducted at only a few locations. They may, therefore, not represent the real NH_3 emissions in practice. This creates a potential uncertainty in the outcome of regional and national NH_3 emission inventories based on emission factors, as dairy husbandry is a major producer of NH_3 (LME, 1999). Also, the relationships between emission levels and such critical variables as the design of the house, the animals' nutrition, and the farm management are poorly understood. This has slowed the development of new dairy cow houses with a reduced NH_3 emission. In the framework of NH_3 emission legislation in the Netherlands, the need for those low emission dairy cow houses will increase in the next few years. In-depth knowledge of the NH_3 emission related processes and critical variables will benefit the design of low emission housing systems, both as individual components and in a system wide approach. It can also facilitate the development of strategies for emission monitoring and control in practical situations, thus being relevant to legislation bodies, researchers, system designers, and agricultural advisors.

2 Goal of the research

The goal of the research in this thesis is to develop and validate a mechanistic simulation model for NH_3 emissions from dairy cow houses. The model should facilitate and support:

- production and assessment of NH_3 emission data (emission factors) for the common dairy cow houses for legislative purposes;
- development of cow houses with low NH_3 emissions as a contribution to cattle farming systems with optimal nutrient management;
- evaluation of NH_3 emissions from the houses in current and innovative dairy farming systems;
- quantification of realistic NH_3 emission fractions for use in emission regional and national emission inventories and studies;

To achieve this multi-faceted goal, the simulation model has to describe quantitatively the pathways of production and volatilisation of NH_3 in the cow house.

3 Nitrogen cycle and ammonia emission in a global perspective

Nitrogen (N) is an essential element in biochemical pathways. Over five billion tons (metric) of N are present in the surface layer of the earth. Less than 2% of this N is in a reactive form (oxidised, reduced) and available for organisms (Mackenzie, 1998). For a long time, natural biological N fixation was the most important way to create reactive N (140 million tons of N per year). However, the contribution of human activities drastically increased with the growth of the global population and the intensification of agriculture. This resulted in doubling of the amount of reactive N by the end of the 20th century (Galloway, 1998).

Nitrogen put in agricultural cycles is partly fixed in animal products and crops. The remainder is lost to the environment, mainly as nitrate (NO_3^-) and ammonia (NH_3), assuming no accumulation in the soil on the longer term (Aarts, 2000). Also, volatile losses by nitrogen gas (N_2) and nitrous oxide (N_2O) will occur. The amount of ammonia emitted to the atmosphere on a global scale is estimated at 54 million tons of N per year (range: 23-88), of which 22 million tons (range: 20-61) originates from animal husbandry. The contribution of cattle husbandry amounts 13 million tons of N per year (Bouwman *et al.*, 1997; Olivier *et al.*, 1998).

4 Environmental consequences of ammonia emission

Nitrogen deposition is in large part related to the emission of NH_3 from agricultural sources and of NO_x from industries, households and traffic. In The Netherlands, with the greatest NH_3 emission per km^2 in Europe (Asman, 1995), NH_3 contributes for about 46% to the deposition of potential acid (Erisman and Draaijers, 1995). Critical loads of acid deposition on natural ecosystems are exceeded in many European countries. As a consequence, eutrophication and acidification occur. Eutrophication has three main effects. Firstly, the composition of the vegetation changes towards N loving species, that supersede the more rare plant species that are typical for ecosystems that are poor in N. Secondly, it leads to nutrient imbalances in the soil, which increase the risk of damage to vegetation by drought, storms, frost, diseases and plagues (Bobbink *et al.*, 1996). Thirdly, surplus N in the form of nitrate leaches to the ground water (Heij & Schneider, 1991).

The acidification aspect of NH_3 deposition is related to the rate of nitrification in the soil. Under the influence of oxygen, nitrifying bacteria transform NH_3 into nitrate (NO_3^-), water and acid (H^+) according to the following chemical reaction (Van Breemen *et al.*, 1982):

$$NH_3 + H^+ \leftrightarrow NH_4^+ + 2O_2 \longrightarrow NO_3^- + H_2O + 2H^+ \qquad [1.1]$$

The net result of this process is the addition of one mole H^+ per mole of NH_3 deposited on the soil after complete nitrification. Soil acidification mainly leads to dissolving of base cations (magnesium, calcium and potassium) and aluminium buffers in ground water. As a consequence, ground water is polluted by leaching of aluminium (Heij and Schneider, 1991).

In addition, high NH_3 concentrations, as observed within a few hundred meters of animal production facilities (buildings, storages) can also cause directly visible effects to vegetation (e.g. brown colouring of the ridges of leaves; Van der Eerden, 1982; Fangmeier *et al.*, 1994).

5 Dutch ammonia emission abatement legislation

To minimise damaging effects on ecosystems, NH_3 emission has to be reduced substantially. The Dutch government has taken legislative measures to achieve a reduction of NH_3 emissions by 70% in the year 2005 relative to an emission level of 216 ktons in 1980 (Van der Hoek, 2000). The year 1980 is the reference year for Dutch NH_3 legislation. New techniques for slurry application and covering of outside slurry storages (Monteny, 1996) have been enforced by law since the late 80's. As a consequence of the measures implemented in practice, NH_3 emission in 1998 was reduced by approximately 23% compared to 1980 (Van der Hoek, 2000). To achieve the 70% goal, additional legislation for animal housing systems is currently being prepared. This legislation has been preceded by the system of Green Label Awards for animal housing systems, which require a 50% reduction compared to traditional housing systems.

In other European countries legislation intended to reduce NH_3 emission from livestock production was developed in the mid nineties (ECETOC, 1994). There is also a recent initiative by the European Commission to set emission ceilings for each individual EU member state. For the Netherlands, the current proposed ceiling is 127 ktons of NH_3 per year. This is a less drastic reduction than the reduction needed to achieve the goal of the Dutch government. Nevertheless, major reductions of NH_3 emissions from all parts of the farming process will be necessary to reach the indicated ceiling.

6 Ammonia in the nitrogen cycle on dairy farms and emission evaluation from cow houses

Today dairy farming is greatly specialised and intensified due to a variety of economic factors, resulting in increased mechanisation and large inputs of nutrients. Mass balances are frequently used to assess agricultural production efficiency in terms of nutrient utilisation. The mean N efficiency of Dutch dairy farms, expressed as the ratio between output and input is 13-16% (Aarts, 2000). Ammonia is one of the output components in the N balance. It originates from the decomposition of N compounds that are present in excreted urine and faeces. In dairy cow houses and on grazed pastures, NH_3 originates from urea, which is converted to NH_3 by the enzyme urease. During indoor and outdoor storage, non-urea N compounds are also decomposed to NH_3 (Patni and Jui, 1991). Emission levels from stores greatly depend on the slurry composition, the climatic conditions (temperature, air velocity), the duration of storage, and the presence of a cover (Olesen and Sommer, 1993). On dairy farms, the stored slurry will generally be applied to the farmer's own crops (e.g. grassland or arable land). The magnitude of the NH_3 emission from slurry application depends on the slurry composition, the application technique, and actual soil and climatic conditions (e.g. Van der Molen *et al.*, 1990). Although great variation exists, the relative contributions of the house (including outdoor storage), slurry application and grazing to the total NH_3 emission from dairy husbandry are 45%, 45% and 10%, respectively, for situations where no emission reduction measures are taken (ECETOC, 1994). In the Netherlands, the relative contribution of the cow houses and outdoor slurry storages in 1998 was estimated at 52% (LME, 1999), due to emission reductions caused by the use of innovative techniques for land application of slurry.

In addition to direct measurements, NH_3 emissions at the farm can be estimated by calculation of the N flows. Most current models used for this purpose are based on emission fractions. An emission fraction represents the amount of NH_3 emitted from each component of the N cycle and is defined as the percentage of the N excreted (cow house, grazing), stored (storage) or applied (slurry application). This approach is used nationally and internationally in emission inventory studies. In the Netherlands, the emission fraction for cows in cubicle houses is normatively set at 14.6% of the total excreted N, whereas the emission fraction is 7.1% for tie stalls (Leneman *et al.*, 1998). At a standardised N excretion of 61.3 kg per cow during an average housing period of 190 days (Van Eerdt, 1998), the per cow emission from the house would amount 8.9 kg N (10.9 kg NH_3) and 4.4 kg N (5.3 kg NH_3) for the cubicle house and the tie stall, respectively. These figures are greater than the measurement based NH_3-N emission levels (nationally referred to as emission factors) of 7.2 (8.8 kg NH_3) and 2.5 kg N (3.0 kg NH_3), respectively. This illustrates the potential discrepancy between measurements and calculations, and the variation that can result from the emission fraction based calculation method. Besides this, a major drawback of emission fractions is their static character, i.e. they can not account for the influence of important variables on NH_3 emissions. The most important variables are related to the cow house design, the diet, the indoor climate, and the management. Mechanistic modelling based on these variables would allow to formulate realistic emission fractions, and thus to improve the method for calculation of the NH_3 emission from cow houses.

7 Ammonia emission models

Models that quantify volatile losses of NH_3 produced from N compounds like urea are commonly used to manage N fertilisation in arable farming systems (e.g. rice production: Rachhpal-Singh and Nye, 1986; Jayaweera and Mikkelsen, 1990), and to evaluate and reduce the emission of NH_3 after application of animal slurry (Van der Molen *et al.*, 1990; Génermont and Cellier, 1997) or from animal houses (Muck and Steenhuis, 1981; Aarnink and Elzing, 1998). These models describe urea conversion, chemical equilibria, and NH_3 mass transfer (diffusion, convection) processes. Muck and Steenhuis (1981) were the first to develop a mechanistic model to quantify the loss of N through NH_3 emission from free stall dairy barns. Their model describes the processes mentioned above for urine applied on a level, solid floor in the walking alley of a cow house. It was adapted by Elzing and Monteny (1997) to evaluate floor and pit related methods that were expected to reduce NH_3 emissions from a cubicle dairy cow house. The model performed well for a scale model of a dairy cow house. The authors indicated that the model had to be extended with modules for the underfloor slurry pit and the urination behaviour of the animals to facilitate research into emission levels and reduction measures in commercial dairy cow houses.

8 Problems to be solved

In the previous sections, the following problems are identified:

- accurate measurement of emission levels from naturally ventilated dairy cow houses is hard to achieve at a reasonable cost. Consequently, data on NH_3 emission levels from traditional houses for dairy cows are few and the development of emission abatement strategies is hindered;
- current NH_3 emission models for dairy cow houses are not adequate to predict and evaluate NH_3 emission levels in practice or to develop options for NH_3 emission control;
- the cow house is an important part of innovative, sustainable dairy farming systems, and integrated nutrient modelling is needed to create and evaluate those systems;
- the emission fraction based calculation method for NH_3 emissions from dairy cow houses insufficiently accounts for important on site variables related to the emission of NH_3.

These problems can be effectively dealt with through the development and the use of a simulation model for NH_3 emissions from dairy cow houses.

9 Overview of this thesis

A literature survey on NH_3 emission and possibilities for its reduction in cattle husbandry was the background of the thesis and is presented in Chapter 2. Chapter 3 describes the basics of the NH_3 production model for cubicle dairy cow houses. It includes a first calibration and validation against measured NH_3 emission in a dairy cow house and a sensitivity analysis for most of the model parameters. As important model improvements, the development of the pH in urine deposited on the floor and the slurry surface, and the air exchange characteristics of slatted floors were then studied. The results are presented in Chapter 4 and 5, respectively. The upgraded model, consisting of NH_3 mass balances for the slurry pit and the floor, is presented in Chapter 6. This chapter also includes a validation of the mass balance for the slurry pit against measured NH_3 concentrations in the pit, and a validation of the whole emission model against measurements in a full scale dairy cow house. Chapter 7 illustrates the potential of the model for calculation of NH_3 emissions in a naturally ventilated dairy cow house, and evaluation of the effect of dairy cow nutrition on NH_3 emissions. The work described in this thesis is discussed in a broader context and concluded in Chapter 8, the General Discussion.

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2

Ammonia emission from dairy cow buildings: a review of measurement techniques, influencing factors, and possibilities for reduction

G.J. Monteny and J.W. Erisman

Netherlands Journal of Agricultural Science 46 (1998): 225-247

Abstract

Because ammonia from livestock production may contribute substantially to environmental pollution, emission from all possible sources (housing systems, manure storage, manure application, outside grazing) should be reduced. Ammonia emission from dairy cow buildings is estimated to be 28% of the total emission from Dutch agriculture. The purpose of this study is to make an analytical inventory of ammonia emission data of dairy housing systems and to assess possibilities for its reduction, based upon the analysis of processes and factors involved in the production and volatilisation of ammonia.

Mass balance methods for the determination of air exchange rates for naturally ventilated dairy cow buildings that are based upon natural or introduced tracers may have good potential for application in emission studies.

In today's dairy husbandry, differences occur in housing system, floor type and manure collection and manure storage system. Ammonia emission levels for cubicle (loose) houses are higher (20-45 g day^{-1} per cow) than for tie stalls (5-27 g day^{-1} per cow), although variation in emissions per housing type are large. Integration of knowledge of ammonia emission related processes and factors will support a more detailed analysis of differences and variation, and will allow an optimisation of possibilities for emission reduction. Substantial emission reductions of up to 50% for cubicle houses with slatted floors can be achieved through each of the following measures: flushing of floors with water or diluted formaldehyde, optimised feeding strategies, and slurry acidification. Highest reductions are possible through V-shaped, solid floors (52%) as a single measure, or in combination with flushing with water (65%) or diluted formaldehyde (80%). Providing that drawbacks are solved, nation wide introduction of one or more these measures will lead to a maximal reduction of the NH_3 emission in The Netherlands with 18kton per year. To achieve the emission reduction goals set by the Dutch government, additional emission reduction for all agricultural sources must be realised.

Keywords: animal nutrition, dairy cattle, environmental pollution, floor construction, legislation, manure treatment, measurement techniques, modelling

1 Introduction

During the past decades, livestock production has been intensified both in numbers of livestock and in production level, following an increased input of minerals through feed stuffs and chemical fertilisers. As a consequence, emission of ammonia (NH_3) to the atmosphere from livestock production related sources (housing systems, manure storage, land spreading of manure, outside grazing) has increased drastically. The emission of NH_3 from agricultural activities in Europe, excluding the former USSR, has doubled between 1950 and 1986 (Asman *et al.*, 1988), whereas for The Netherlands this increase was by a factor 2.5 (ApSimson *et al.*, 1987). This increased NH_3 emission has substantially contributed to the exceeding of critical loads for nitrogen (N) deposition in many European countries, leading to eutrophication and soil acidification related environmental stress (Heij & Schneider, 1991; Heij & Erisman, 1997). In The Netherlands, for example, about 46% of the potential acid deposition is caused by emission of NH_3 (Erisman & Bleeker, 1997), mainly originating from agriculture (Anonymous, 1996). To avoid NH_3 related environmental damage, its emission must be reduced with 70% in 2005 relative to the emission level in 1980 (204 kton; Anonymous, 1996), being the reference year for Dutch NH_3 legislation. In 1995, 60% of the Dutch agricultural NH_3 emission originated from cattle husbandry. Ammonia emission from cattle housing systems, including storage, was estimated at 45 kton (37 kton for dairy; 8 kton for other cattle) in 1995, being approximately 34% (28% for dairy) of the national emission (Anonymous, 1996). In addition to the law enforced advanced slurry application techniques and covering of outside slurry storages, legislation is prepared for animal buildings with low emissions to achieve the reduction goals.

Improved and structured knowledge of NH_3 related processes and factors can be used as a tool to improve insight in differences in levels of NH_3 emission and to support legislation concerning and research into optimisation of emission abatement strategies for cattle buildings. The availability of accurate methods for measurement of NH_3 emissions from agricultural sources is important in the framework national and international emission studies (Asman, 1995; Anonymous, 1994a) and for strategic monitoring and research purposes (e.g. assessment of emission reduction measures). Naturally ventilated animal buildings, being the most common type of dairy cow housing, require in this framework special attention, because of the technical complexity of measurement of its ventilation rates.

The objective of this paper is a literature-based discussion on the origin of NH_3 release in dairy cow buildings and possibilities for measurement and abatement of NH_3 emissions. In this perspective, the following issues are addressed:

- theory of NH_3 development in dairy cow buildings;
- state of the art in measurement technology for animal buildings;
- inventory of current housing systems for dairy cows and their NH_3 emissions;
- possibilities for reduction of NH_3 emission based upon the way they interfere with emission related processes and factors;
- synthesis and conclusions.

2 Processes and parameters influencing NH_3 release in dairy cow buildings

2.1 Nitrogen excretion in faeces and urine

Nitrogen plays a basic role in the life cycle, physiological processes, production and body maintenance of animals. All N, taken up with the feed, not retained in the animal body is excreted through faeces and urine. Tamminga (1992) estimated that, of the daily N intake by an average Dutch dairy cow, 29% is excreted in faeces, 50% in urine and 19% in milk, while 2% was deposited in body reserves. Non-protein N compounds, mainly being in the form of urea, are excreted with urine. Ammonia in dairy cow buildings is for the largest part produced following urea hydrolysis (Muck & Steenhuis, 1981). The amount of urea N relative to the total N content of dairy cow urine depends on physiological factors like diet composition and production level and is between 59-89% for cattle fed with grass or grass and maize silage, including protein supplement (Bristow *et al.*, 1992). An increasing surplus of degradable protein in the diet will result in a higher rate of N excretion with urine (Van Vuuren *et al.*, 1993), whereas the volume of urine produced is related to the intake of N, potassium (K) and sodium (Na) (Van Vuuren & Smits, 1997). This volume will affect the urination frequency of the animals. Whitehead (1995) made an inventory of urine production (volume, urination frequency) by dairy cows and of typical values for faecal and urinary N excretion. In this inventory, covering many international literature sources, it is discussed that all parameters mentioned above show a large variation, mainly related to differences in diet (including water consumption), production level, breed and management. Urine production, urination frequency, urea N concentration in urine and N excretion with urine, expressed per cow, range from 10-40 L day^{-1}, 8-12 day^{-1}, 2-20 g L^{-1} and 80-320 g day^{-1}, respectively. Faeces mainly contain organic N compounds (e.g. undigested protein; daily N excretion 50-200 g per cow). Ammonia production from these compounds in dairy cow buildings is relatively unimportant (Muck & Steenhuis, 1982), because of low mineralisation rates. Mineralisation may play a role when the slurry is stored, either inside or outside the house, for longer periods of time and especially at higher temperatures (Patni & Jui, 1991).

2.2 Urea hydrolysis

Urea hydrolysis, catalysed by the enzyme urease, follows the Michaels Menten kinetics for basic enzymatic conversion processes (see e.g. Muck & Steenhuis, 1981). Urease is produced by micro organisms that are abundantly present in faeces and thus also upon surfaces that are frequently fouled with faeces, like floors (Ketelaars & Rap, 1994). The following equation represents urea hydrolysis in a liquid environment (e.g. urine on the floor, urine in the straw bed or slurry in the pit):

$$CO(NH_2)_2 + H_2O \xrightarrow{\text{urease}} 2NH_3 + CO_2 \qquad [2.1]$$

The rate of urea hydrolysis and thus the ammonium production rate depend on the urea concentration in the urine and the maximal rate of enzymatic urea hydrolysis at high urea concentrations, also called 'urease activity'. Urease activity is temperature related. Muck & Steenhuis (1981) reported complete urea conversion within 1 day after urine deposition upon fouled floors at temperatures above freezing point. Furthermore, Elzing & Monteny (1997a) showed that all urea in urine applied on a fouled slatted floor element was converted within approximately two hours at temperatures of 10 °C or higher. This means that urea hydrolysis is completed fast under conditions found in practice. Moreover, urease activity levels in commercial dairy cow buildings are very high (Braam & Van den Hoorn, 1996), making the substrate (urea) availability the limiting factor. Measures that reduce emissions from fouled floors will therefore have to focus on lowering the initial urea concentration in the urine via nutrition or very frequent dilution (e.g. by flushing floors with water) or on a drastic reduction of the urease activity.

2.3 Dissociation

In the liquid, ionised (ammonium; NH_4^+) and unionised ammonia (NH_3) equilibrilize (Equation 2.2):

$$NH_3 + H_2O \xleftrightarrow{pH, T} NH_4^+ + OH^- \qquad [2.2]$$

The amount of NH_3 relative to total ammoniacal N (TAN: sum of NH_3 and NH_4^+) in the liquid is determined by the, positively with temperature ('T') related, acid dissociation constant (K_a) for NH_3 and by the pH (Loehr, 1973). For NH_3 dissociation in aqueous solutions at 20 °C, K_a is $3.982*10^{-10}$ (Weast *et al.*, 1986), whereas for more concentrated solutions, like slurries, an adapted - much lower - K_a-value was found ($0.81*10^{-10}$; Hashimoto, 1972). The influence of pH is very pronounced. At pH values below 6-7, nearly all TAN in the liquid is present in ionised, non-volatile form (NH_4^+). Above pH 7, the fraction of NH_3 increases greatly and at pH values of 11 or higher TAN is mainly in the form of NH_3. Data reported by Elzing & Monteny (1997a) showed that the urine on a fouled floor has a pH of around 8.6, whereas that value was also assumed for the pH of the top layer of slurry in the pit, being the place where volatilisation takes place. At these pH levels, up to 50% of TAN is present in the form of volatile NH_3 (Groot Koerkamp & Elzing, 1996), mainly depending on temperature. Acidification of slurry and urine to a level of below pH 6 is the most effective way to lower the NH_3 release.

2.4 Volatilisation

Volatilisation of NH_3 is convective mass transfer from the boundary of urine or slurry and air to the air above the floor or above the slurry in the pit. The amount of volatile NH_3 depends on equilibrium between NH_3 in the liquid ('l') and in the gas phase ('g') at that boundary (Equation 2.3), following Henry's Law:

$$NH_3(l) \xleftrightarrow{T} NH_3(g) \qquad [2.3]$$

This equilibrium is strictly temperature dependent; higher temperatures result in a higher amount of gaseous NH_3.

Ammonia volatilisation rate (Equation 2.4) is the product of the NH_3 mass transfer coefficient and the difference in concentration or partial pressure of gaseous NH_3 ('g') between boundary ('bound') and air above the boundary ('air').

$$NH_3(g, bound) \xleftrightarrow{T, v} NH_3(g, air) \qquad [2.4]$$

The mass transfer coefficient for NH_3 depends on temperature ('T') and air velocity ('v') at the boundary. Haslam *et al.* (1924) developed a general relationship for a film reactor. It was found to be applicable for dairy cow housing systems too (Muck & Steenhuis, 1981). More empirically determined mass transfer coefficients for NH_3 in the framework of animal husbandry emissions research were reported in recent studies (Svensson & Ferm 1993; Arogo *et al.*, 1996), but their application was not studied for other conditions and situations than that they were developed for.

Elzing & Monteny (1997a) showed that, at values for urease activities found in dairy cow buildings, NH_3 volatilisation is the highest at approximately two hours after urine deposition upon floors. Furthermore, NH_3 volatilisation from a urine puddle was found to continue for 15 hours or more, depending on environmental conditions. Interfering in the volatilisation process itself to reduce NH_3 release in dairy cow buildings will have to focus on reducing temperature, through cooling of floor and slurry surfaces, and air velocity, by minimisation of airflow inside the building.

3 Measurement techniques for NH_3 emission from livestock buildings

The emission of NH_3 from a building is defined as the product of air exchange rate and the difference in NH_3 concentrations in incoming and exhaust air. Methods and equipment for measurement of air exchange rates and gas concentrations are discussed below.

3.1 Air exchange rates

Direct methods

For mechanically ventilated animal buildings, the anemometer or measurement ventilator installed in the ventilation shaft (Van Ouwerkerk, 1993) is commonly used to determine air exchange rates directly. Wind tunnel calibration is necessary to relate the anemometer response (rotations per time unit) with the actual air exchange rate.

Continuous monitoring of pressure differences over all ventilation openings of the building is useful as a direct method for naturally ventilated animal buildings. The basis of this method is Bernoulli's Law, relating the ventilation rate over an opening to the surface area of the opening and the square root of the pressure difference over the opening (Van Ouwerkerk, 1993). It is still in an experimental stage.

Indirect methods

Indirect methods, using heat balances or tracer gas mass balances, have become ready for use during the past years. The basic principle of the heat balance method (Van 't Ooster *et al.* ,1994; Van Ouwerkerk, 1993) is that the change in temperature of the air volume inside the building is the net result of heat production (e.g. by animals or external heating) and heat losses, mainly through convective heat transfer through the structure, and ventilation. To calculate ventilation rate, all other heat production and loss terms have to be known. Ventilation rate for a certain time step directly follows from measured changes in air temperature inside the building per time unit, given the effective heat capacity of the air inside the building.

The principle of mass balance methods for tracer gasses is basically the same as for the heat balance approach. The ventilation rate follows from the net result of tracer gas production and losses, assuming no gas transport through the construction elements of the house. Depending on the goal of the measurements, methods for natural and synthetic tracer gases are:

- a variable, known production rate, e.g. when production rate from the source of the tracer gas cannot be controlled (natural tracer gas);
- a constant production rate (continuous dosage of a synthetic tracer gas);
- rate of decay (certain amount of synthetic tracer gas introduced in the house at t=0).

In the framework of emission surveys, continuous determination of the ventilation rate is required. This makes the first two methods the most appropriate. In Van Ouwerkerk (1993), a detailed description is given of the variable production rate method using the CO_2 mass balance. This method requires a CO_2 production model for animals (Van Ouwerkerk & Pedersen, 1994). Introduced tracer gases like carbon monoxide (CO; Demmers *et al.*, 1998), sulphur hexa fluoride (SF_6) and nitrous oxide (N_2O) can be used in the method of constant production rate.

3.2 Measurement equipment for gas concentrations

Tracer gases

Van 't Klooster *et al.* (1996) give an overview of technical possibilities for the measurement of tracer gas concentrations in the framework of NH_3 emission studies. For the purpose of accurate measurement of emission levels or process studies, N_2O, CO and CO_2 concentration can be measured best with monitors based upon the Non Dispersive Infra Red principle (NDIR). Basic elements of such monitors are an infrared emitter and receiver. Different gasses show absorption of specific wavelengths in the infrared spectrum. The measured absorption or extinction in the IR-spectrum is a direct measure for the concentration of the gas under survey. They can be used for specific gases (Demmers *et al.*, 1998), when using the appropriate filters, or for multi gas measurements (Van Ouwerkerk, 1993). Cross sensitivity with e.g. water vapour may affect measurement accuracy. When SF_6 is used, concentrations need to be measured with a gas chromatograph.

Ammonia

Besides NDIR monitors, a nitrogen oxide (NO) monitor in combination with a high temperature catalyst stainless steel converter is commonly used in The Netherlands for continuous measurement of NH_3 concentrations in livestock buildings. This method is described in detail by Van Ouwerkerk, 1993 and Groot Koerkamp *et al.*, 1998. In the catalyst converter, NH_3 is converted to NO. The main reason for this is that NO is reasonably inert, while NH_3 in the air sampling tubes may be lost e.g. by dissolving in water drops or absorption at the tube surface. NO monitors use the principle of a chemo-luminescence reaction between NO and ozone. Wyers *et al.* (1993) describe the development and application of a continuous flow denuder for NH_3 concentration studies, basically for ambient NH_3 concentration levels but also for a wider application (e.g. in livestock buildings; Van Ouwerkerk, 1993). It has a much lower detection limit than the measurement techniques described previously. The basic process in a denuder is chemical absorption/desorption using counter flows of sampled air and acid absorption solutions. After a desorption procedure, the NH_3 concentration is measured on-line conductometrically.

When continuous measurement of NH_3 concentration is not required, a system of continuous air sampling and accumulation in an acid solution (e.g. nitric acid) in combination with titrimetric determination of the amount of NH_3 captured afterwards in a laboratory or accumulation in passive samplers can be used (Van Ouwerkerk, 1993).

3.3 Evaluation

The advantage of the heat balance is the fact that only the air temperature inside the building has to be measured, which is fairly simple compared to measurement of tracer gasses. Drawbacks are related to the need for models to predict heat production terms (animals) and losses through the surrounding structure.

Assuming no gas transport through the structure, advantages of the use of tracer gases lie in the limited number of loss terms, since this can only be through ventilation (assuming no accumulation in manure, the animal or parts of the internal structure). On the other hand, the density of the tracer gas should be close to air density to allow the assumption of perfect mixing. When using the CO_2 mass balance, no tracer gas has to be introduced in the building, meaning that the measurement system can be restricted to gas sampling and analysis only. When synthetic tracer gasses are used, a dosage system has to be installed and operated. Moreover, synthetic tracer gasses may have other drawbacks like toxicity (CO), specific masses differing from air (N_2O, CO) and the possibility of gas production from unknown or unexpected sources (N_2O; nitrification/denitrification of nitrogen compounds).

Scholtens *et al.* (1996) validated the use of CO_2 and CO mass balance methods against the method of anemometers placed in the exhaust shafts in a mechanically ventilated dairy cow building. The CO_2 method underestimated the ventilation rate by 18%, whereas the CO method showed no significant difference with the anemometer method. The model for CO_2 production by the animals (Van Ouwerkerk & Pedersen, 1994) was found to be the most important source of the underestimation by using the CO_2 mass balance (Scholtens *et al.*, 1996). Van Ouwerkerk & Pedersen (1994) proposed to increase the respiration quotient to improve the CO_2 production model for dairy cows. Demmers *et al.* (1998) showed that applicability of the CO mass balance is quite good, except under conditions of high ventilation rates in naturally ventilated buildings. Under these conditions, mainly caused by high outside wind speeds, the difference in CO concentrations between air entering and leaving the building appeared to be too small to be measured accurately and thus to allow accurate estimation of the ventilation rate.

For continuous and exact measurement of NH_3 emissions from mechanically ventilated buildings, an anemometer in combination with the converter + NO monitor or a NDIR monitor is to be preferred, whereas the combination of synthetic tracer gas and specific monitors is the best procedure for naturally ventilated buildings.

Besides methodology and measurement technique, measurement strategy (design of hardware and protocol for measurements) is of great importance when carrying out emission studies for naturally ventilated cow buildings. Incomplete mixing of volumes of air inside the house leads to spatial variability in gas concentrations. This aspect has to be studied before the measurements start in order to design the sampling system (number and location of sampling points) for air inside the house correctly. When designing the protocol for measurements, detailed knowledge of the emission process benefits minimisation of the number of measurements and its duration. Mechanistic modelling of the processes relevant for NH_3 emission (Muck & Steenhuis, 1981; Monteny *et al.*, 1998) and the application of statistics (De Boer, 1993) may contribute to this.

4 Dairy cow buildings: floor and manure handling systems, and NH_3 emission

Two main types of housing systems for dairy cows can be distinguished: loose housing and tie stalls. In loose housing, the two major sub-systems are cubicle housing systems and non-cubicle or (deep) litter and straw systems. Functional elements of loose housing systems are a non-restricted (open, straw bed) or partly restricted (cubicles) lying area, a walking area and a feeding area. For tie stalls systems, these functional elements are combined (Anonymous, 1994b). Floor type, manure handling and indoor manure storage facilities are the major characteristics that are relevant from NH_3 emission point of view. Table 2.1 presents an overview of dairy cow housing systems, subdivided by these characteristics. Except for straw based systems where farmyard manure (FYM) is produced, manure is present in the form of slurry. Ammonia emission data are given to the extent that reliable data were available from different literature sources. Conditions under which the measurements were carried out (ventilation system; measurement principle of ventilation rate and indoor temperature) are reported. Data are discussed in the following paragraphs.

Table 2.1: Housing systems for dairy cows, floor, manure handling and manure storage characteristics, NH_3 emission (g day^{-1} per cow) and measurement conditions.

Housing	Floor	Manure	Manure	NH_3	Ventilation		Reference
system	type	handling	storage	emission	system*1)	method *2)	
Loose housing							
Cubicle	Slats	No	Deep pit	32-45	M	Anemom	Kroodsma *et al.*, 1993
				20-42*3)	N	CO_2	Groot Koerkamp *et al.*, 1997
				40	N	CO_2	Van 't Ooster, 1994
				26	N	Estimate	Pfeiffer *et al.*, 1994
	Flat, solid	Scraping	Outside	25	N	Estimate	Pfeiffer *et al.*, 1994
				32	N	CO	Demmers *et al.*, 1998
	Sloped, solid	Scraping	Deep pit	25*4)	M	Anemom	Huis In 't Veld *et al.*, 1994
Non-cubicle	Flat, solid	Tractor	Outside	30	M	Anemom	Groenestein & Reitsma, 1993
Tie stalls							
	Slats	No	Deep pit	9-14	M	Anemom	Groenestein & Montsma, 1991
			Shallow pit	5-12	N	Estimate	Mannebeck & Oldenburg, 1990
				6-21*3)	B	CO_2	Groot Koerkamp *et al.*, 1997
	No, gutter	Scraping	Outside	27	N	Estimate	Pfeiffer *et al.*, 1994

*1): M = mechanical ventilation; N = natural ventilation; B = both ventilation principles.
*2): Anemom = anemometer; CO_2, CO = gas mass balance method; Estimate = estimated air exchange rates.
*3): Emission data corrected for mean outside temperature.
*4): Emission standardised for 15 °C.

4.1 Loose housing systems

Cubicle houses with slatted floors are the most common for dairy cows in The Netherlands (Anonymous, 1995) and some other European countries (Anonymous, 1994a). Inside, under floor pits are present for slurry storage. Kroodsma *et al.* (1993) found NH_3 emission from a mechanically ventilated cubicle house varying from 32 to 45 g day^{-1} per cow at an inside air temperature range of 12 to 18 °C. Groot Koerkamp *et al.* (1997) measured NH_3 emissions from 16 cubicle dairy cow buildings during a large survey in 4 European countries (UK, The Netherlands, Denmark, and Germany). Ammonia emission was measured during 24 h under winter and summer conditions. After correction for mean outside temperature, average NH_3 emission per country ranged from 20 (Denmark) to 42 (The Netherlands) g day^{-1} per cow. The observed variation between 4 similar dairy cow buildings per country and between countries can be regarded as a combination of systematic and natural variation, mainly caused by differences in climate, diets, details in the building designs and management. Other emission data for naturally ventilated cubicle buildings with slurry storage beneath the slatted floor were found to amount 40 g day^{-1} per cow (Van 't Ooster, 1994) and 26 g day^{-1} per cow (Pfeiffer *et al.*, 1994). Emission data were not corrected for temperature.

Inclined shallow pits beneath the slats are common for cubicle houses in the US (Collins & Wilson, 1994). In these systems, slurry is continuously removed from the house by gravity and stored outside, e.g. in a slurry lagoon. Emission data in literature were lacking for such housing systems.

Cubicle housing systems with flat or sloped solid floors are found in various countries. A solid floor type implies that faeces and urine have to be removed regularly (e.g. with scrapers) and collected in an under floor pit or in an outside storage. When a flat solid floor is present, there may be a longitudinal incline towards a dorsally situated collection gutter to allow slurry removal by flushing and additional outside storage (e.g. in a lagoon; Fulhage & Martin, 1994). Ammonia emission levels for cubicle houses with flat solid floors with scrapers and outside slurry storage of 24.5 and 31.6 g day^{-1} per cow were reported by Pfeiffer *et al.* (1994) and Demmers *et al.* (1998), respectively. Data were not corrected for temperatures. Sloped, solid floors may be designed V-shaped, with a lateral slope, so urine is drained through a small gutter, longitudinally situated in the middle of the floor (Swierstra *et al.*, 1995). The slope may also be to one of the sides of the walking alley (Moore & Hegg, 1980). Ammonia emission for a V-shaped solid floor with a 3% lateral slope was 24.5 g day^{-1} per cow, corrected for a reference temperature of 15 °C (Huis in 't Veld *et al.*, 1994).

Non-cubicle loose housing systems, operated with a straw bed or a concrete floor, are less common than loose housing systems with cubicles. When a straw bed is used, faeces and urine collected often remain in the house for a longer period of time. Removal of the collected faeces and urine - indicated as farm yard manure (FYM) - can be by hand or by a scraper attached to a tractor. Ammonia emission for a mechanically ventilated house containing 40 dairy cows and 18 head of young stock, at an average temperature of 9 °C, was on average 30 g day^{-1} per animal (not corrected for temperature; Groenestein & Reitsma, 1993).

4.2 Tie stalls

In tie stalls, faeces and urine are collected either as slurry in an under floor pit covered with concrete or steel slats, or in a shallow gutter where faeces and urine are separately collected. In the US, tie stalls are often equipped with inclined shallow pits beneath the slats (Graves *et al.*, 1984). Removal of the faeces, optionally collected in a layer of straw in the gutter (FYM), is carried out by hand or by a scraper, whereas urine is drained off by gravity. FYM is usually stored outside. Daily NH_3 emission for a commercially operated, mechanically ventilated tie stall for dairy cows, with slurry storage in a pit with a depth of 1 m behind the animals, varied with temperature (15 to 19 °C) from 9 to 14 g per cow (Groenestein & Montsma, 1991). Ammonia emission from 16 naturally and mechanically ventilated tie stalls, observed in 4 European countries in the framework of the international survey described previously, varied from 6 to 21 g day^{-1} per cow (corrected for mean outside temperature) (Groot Koerkamp *et al.*, 1997). Based upon an estimated ventilation rate, Mannebeck & Oldenburg (1990) and Pfeiffer *et al.* (1994) reported emissions of 5 to 27 g NH_3 day^{-1} per cow (not corrected for temperature) for a large number of naturally ventilated tie stalls, measured under various outside temperatures. As described for emissions from cubicle housing systems, ranges in NH_3 emission from tie stalls observed appear to be large due to systematic and natural variation in emission determining factors.

5 Measures to reduce NH_3 emission from dairy cow buildings

Measures that reduce the NH_3 emission from a dairy cow house are based on engineering, nutrition or management. They influence one or more of the parameters that play a role in the emission related processes. Main themes are:

(1) reduction of the urea concentration of urine by nutritional measures;
(2) dilution of urine on floors and removal from floors
(3) slowing down the urea hydrolysis on floors;
(4) control of pH;
(5) reduction of mass transfer of NH_3 from urine and slurry;
(6) reduction of air exchange between pit and house.

5.1 Reduction of the urea concentration of urine by nutritional measures

Altering the diet is regarded as an effective and direct way of achieving a reduction of the urea concentration in the urine. Smits *et al.* (1995) compared the effect on the NH_3 emission of two diets in a commercial cubicle house with 34 lactating, highly yielding dairy cows in a repetitive experiment over 126 days. The diets differed in nitrogen content, resulting in a daily intake per cow of rumen degradable protein (RDP) with the "low-N" diet of 40 g, and of 1060 g with the "high-N" diet. Salt was added to the low-N diet to obtain similar urine production volumes. As a result, the concentration of urea nitrogen for the low-N diet was 42% lower than for the high-N diet, whereas the emission of NH_3 was reduced with approximately 39%. The results are in good accordance with the findings by Elzing & Monteny (1997b). They reported a linear relation between the urea concentration and the NH_3 emissions in trials, conducted in a scale model of a dairy cow house, where a fouled slatted floor element was sprinkled with urine from groups of lactating cows fed with different diets. In another experiment (Smits *et al.*, 1997) similar to the one mentioned previously (Smits *et al.*, 1995), salt was added to the high-N diet to increase both N excretion in urine and urine production, at a comparable urinary urea concentration. The emission reduction by the low-N diet was approximately 20%, mainly caused by the reduced number of urinations per cow.

5.2 Dilution and removal of urine on floors

Indirect lowering of the urea and TAN concentration is achieved through flushing floors. Adding water results in a dilution of the urine on the floor and of the slurry in the pit. Besides dilution, removal of urine from the floor surface is a feature of flushing systems. The frequency of the flushing actions and the amount of water used per flushing determine the potential NH_3 emission reduction. Frequent flushing results in more frequent removal of urine, whereas flushing with more water results in an increased dilution of the urine.

By flushing slatted floors, NH_3 emission was reduced by a maximum of 17% (De Boer *et al.*, 1994; Ogink & Kroodsma, 1996). Even though different amounts of water (up to 110 L day^{-1} per cow) and flushing intervals (once every 1-3.5 h) were used, no relationship was found between emission reduction and those variables. Relative to unflushed slatted floors, spraying a V-shaped solid floor with 6 L of water day^{-1} per cow at a scraping and flushing frequency of once every two hours resulted in a 65% reduction of the NH_3 emission was reported by Braam *et al.* (1997b). The effects of amounts of water used and flushing and scraping frequencies on the emission reduction for a V-shaped solid floor were reported by Huis in 't Veld *et al.* (1994) and De Boer *et al.* (1994). They reported that flushing with 50 L of water day^{-1} per cow every 2 hours directly after the scraping action resulted in an emission reduction of 34% compared to only scraping of the solid floor. Increasing the scraping and flushing frequency to once every hour did not result in a significant higher emission reduction. Emission was reduced to 14% at a reduced water use to 28 L day^{-1} per cow combined with an increased scraping and flushing frequency of once every hour (Huis in 't Veld *et al.*, 1994). From this data we may conclude that, contradictory to findings for slatted floors, emission reduction and water use are positively correlated for sloped floors.

At flushing frequencies mentioned above, flushing will not have had a major effect on the urea hydrolysis process through dilution of urea, because urea is usually hydrolysed within 2 h after urine deposition on floors. To be effective from that point of view, continuous flushing would have to be operated or the flushing frequency would have to be related to the urination frequency. Both options were for technical reasons not investigated.

5.3 Slowing down urea hydrolysis

Slowing down the urea hydrolysis process can be achieved through temperature reduction or inhibition of the enzyme urease. For dairy cow buildings, data on cooling of floor and slurry surfaces and effects on NH_3 emission were lacking in literature. Urease inhibitors are well known in rice production (Keerthisinghe & Freney, 1994) and are sometimes used to lower NH_3 emissions from feedlots (Varel, 1996). Their applicability in cow buildings has not been investigated. Emission reduction data were obtained from experiments on flushing floors with diluted formaldehyde. Scraping and flushing were combined and conducted hourly and every two hours, respectively. NH_3 emission reduction for slatted floors and V-shaped solid floors, relative to the emission from a cubicle house with slats, was 50% (Ogink & Kroodsma, 1996) and 87% (Bleijenberg *et al.*, 1995) respectively, using daily volumes of 19 L and 34 L of a diluted formaldehyde solution per cow. These data indicate that urea hydrolysis had been reduced to very low values. Furthermore, Ketelaars & Rap (1994) successfully removed floor-bound urease activity in dairy-cow houses by rinsing the floor with a hydrochloric acid solution, consequently reducing NH_3 emission to very low values.

5.4 Control of pH

Lowering the pH at the emitting surfaces (floor, slurry in the pit) by addition of acid has shown to be quite effective in reducing NH_3 emissions from slurry. A reduction of 37% was reported by Bleijenberg *et al.* (1995) in experiments where pH of the slurry, stored in a pit under the slatted floor, was reduced to 4-4.5 by regular addition of nitric acid. Even higher reductions of up to 60% were achieved by a combination of acidification of slurry in a shallow pit and regular flushing of the slats with the acidified slurry (Kroodsma & Ogink, 1997).

5.5 Reduction of mass transfer

Possibilities for influencing convective mass transfer of NH_3 are through reduction of temperature and air velocity at the emitting surfaces (floor and slurry) and of the area of the emitting surface (Elzing & Monteny, 1997b). Findings with temperature reduction are previously described. Influencing air velocity in naturally ventilated cow buildings is hard to achieve, because a system for regulation of the ventilation rate is not present or not operated. Except through solid floors, possibly leading to a reduction of air velocity in the pit (see Paragraph 5.6), reducing air velocities by climatisation is therefore not regarded to be a practical option for emission reduction.

Reduction of the area of floors and pit is only possible when the housing system is changed. NH_3 emission was reduced by approximately 10% when the fouled floor area per cow was reduced from 3.5 to 2.5 m^2 in an adapted design for a dairy cow house with cubicles (Metz *et al.*, 1995). For a tie stall with a fouled floor area of approximately 1 m^2 per cow and a reduced pit area, emission reduction was 28% compared to a cubicle house (Metz *et al.*, 1995).

5.6 Reduction of air exchange between pit and house

The area for air exchange between the pit and the air inside the house depends on the floor type used (Braam *et al.*, 1997a) and by parameters causing air exchange (e.g. ventilation system, stack effect due to temperature gradients between slurry and inside air; see e.g. Bruce, 1975). For slatted floors, this area is approximately 20-25% of the total floor area (Anonymous, 1989). In cow buildings equipped with solid floors, the only possibility for air exchange is through the openings at each end of the alleys through which scraped slurry is deposited in the pit. Intermediate openings might be required if floor length increases. The reduced air exchange is an important factor in the emission reduction for this type of floors relative to slatted floors. As a consequence of reduced air exchange, transport of NH_3 volatilised to the air inside the pit to the air inside the house is hindered (Braam *et al.*,1997b). Furthermore, it might also cause lower air velocities at slurry level, leading to a lower volatilisation (Elzing & Monteny, 1997b). Also the accumulation of NH_3 in the air inside the pit may contribute to a reduced volatilisation. Swierstra *et al.* (1995) reported emission reductions between 48% and 52% for solid, V-shaped floors. Similar reductions were found by Braam & Van den Hoorn (1996), for the same floor but with high slurry level and a wooden construction to prevent airflow in the pit. Comparability of those data is hard, because of differences in experimental conditions (season, year).

Table 2.2 presents a schematic overview of the interaction between NH_3 emission reducing measures and processes and parameters. In this overview, emission reduction potential is expressed relative to dairy cow buildings with cubicles, slatted floors and under floor slurry storage.

Table 2.2: Overview of the working principle of emission reducing measures and reduction of the NH_3 emission reported in literature (in % compared to slatted floors).

Measure	Process involved	Control factor	Maximal reduction	Reference
Feeding strategies	urine and faeces production	urea concentration	39	Smits *et al.*, 1997
Slurry handling:				
* flushing with water	enzymatic conversion	urea concentration	17	Ogink & Kroodsma, 1996
* formaldehyde flushing	enzymatic conversion	urease activity	50	Ogink & Kroodsma, 1996
* slurry acidification	dissociation	pH	37	Bleijenberg *et al.*, 1995
+ additionally flushing slats with acidified slurry	dissociation	pH	60	Kroodsma & Ogink, 1997
Floor systems:				
* V-shaped solid floors	air exchange/ volatilization	air velocity	52	Swierstra *et al.*, 1995
+ flushing with water	enzymatic conversion	urea concentration	65	Braam *et al.*, 1997b
+ formaldehyde flushing	enzymatic conversion	urease activity	80	Bleijenberg *et al.*, 1995
Housing systems:				
* reduced slatted floor area	volatilization	emitting area of floor/pit	10	Metz *et al.*, 1995
* tie stalls	volatilization	emitting area of floor/pit	28	Metz *et al.*, 1995

6 Prospects of different emission reducing measures

6.1 Nutrition

Practical possibility for reduction of the nitrogen excretion in urine is replacement of a part of the grass silage in the cow's diet by feed stuffs with a low nitrogen content, e.g. maize (Valk *et al.*,1990; Dewhurst & Thomas, 1992). However, dairy cow diet manipulation to reduce NH_3 emission should focus on lowering the urinary nitrogen concentration in the urine by lowering the N surpluses in the diet rather than by increasing the volume of urine produced or the frequency of urination (e.g. through the addition of salt; Smits *et al.*, 1997). In that perspective, the intake of water, induced by the amounts of N and salts in the diet is of importance.

Other possibilities for the reduction of the nitrogen content of the diet are through improved grassland management and grazing. Bussink (1994) showed that reduction of the N fertilisation rate of grassland resulted in a significantly lower NH_3 emission during grazing of dairy cows. This was mainly caused by a reduced excretion of N. Expectedly, feeding of grass silage from the grassland with the reduced fertilisation rate will also reduce NH_3 emission in the dairy cow house. However, no data are available to support this. Bussink & Oenema

(1998) calculated that part time grazing during the summer (cows kept inside during night) leads to an increase in NH_3 emission on a farm scale by 10% compared to full time grazing. Because the cows then stay inside the house for a longer period of time, more slurry (faeces and urine) is produced inside the house, causing extra emission from the house. Moreover, because more slurry needs to be applied to the field, emission from land spreading increases.

6.2 Flushing systems

A major drawback of flushing is the amount of water added to the slurry. At an average daily slurry production of 50 L per cow, flushing of slatted floors would cause and increase in slurry volume of up to 200%. This increase is less pronounced but still considerable for flushing solid, V-shaped floors (10-100%). Besides investment costs for the technology, storage and application of this extra slurry volume will also lead to additional operational costs. Flushing with diluted formaldehyde solutions allows use of much less water, because the reduced urease activity is more important than dilution or removal of urine. A disadvantage of the use of formaldehyde is a potential for the emission of formaldehyde gas to the inside air, which might have negative health effects. Safety risks could be minimised when indoor air concentrations can be related to the concentration of formaldehyde in the flushing solutions and when other relevant conditions (e.g. temperature) and limits for concentrations of formaldehyde gas in work-place environment (Ogink & Kroodsma, 1996) are taken into account.

6.3 Control of pH

Reduction of pH through slurry acidification is an effective way to reduce NH_3 emissions. Although different organic and inorganic acids could be used, experiments were only carried out using nitric acid. This was done basically from the point of view of possible substitution of additional chemical fertilisers by slurry mixed with nitric acid. However, due to the risk of denitrification of the nitrate added and consequently emission of the environmentally harmful N_2O, pH had to be kept below 4.5. The amount of nitric acid needed to achieve that pH value leads to slurry with high nitrogen contents (e.g. around 9 g N kg^{-1}; Bleijenberg *et al.*, 1995). In order to prevent the risk of extra nitrate leaching when using acidified slurry for (grassland) fertilisation, advanced application technology for small amounts of slurry is required to match N fertilisation rates with the N demand of the grassland. Organic or other inorganic acids may be an alternative. However, no literature was found relative to dairy husbandry.

6.4 Housing systems

NH_3 emission per cow for tie stalls (5-27 g day^{-1}) tend to be lower then for loose housing systems with cubicles (25-45 g day^{-1}). The emission reducing effect in tie stalls is mainly caused by a reduction of surface area of the pit and the, urine and faeces fouled, floor. Drawbacks of tie stalls are generally related to a higher labour demand, especially for milking and feeding. Furthermore, newly built tie stalls will be forbidden or it is in discussion in some countries (e.g. Switzerland) from the point of view of animal welfare. In that perspective, important topics are freedom of movement for the cows and possibilities to conduct natural behaviour. These requirements are met in systems with loose housing on straw, although NH_3 emission for this type of dairy housing (one measurement) might be near cubicle house emission levels. In addition, Groenestein & Reitsma (1993) found methane emissions of approximately 1 kg day^{-1} per cow for these systems. This is substantially higher than average methane emissions from slurry based dairy cow housing systems (0.15-0.37 kg day^{-1} per cow; Crutzen *et al.*, 1986; Van der Hoek, 1984) and may be related to anoxic degradation processes in the straw bedding. An evaluation of housing systems in the framework of NH_3 emission, therefor, needs to be extended with animal welfare and other environmental aspects.

6.5 Floor systems

Compared to slatted floors, longitudinal V-shaped solid floors have a potential for a lower NH_3 emission (52%) as can be concluded from data presented in Table 2.2. This statement might be questioned when emission levels reported for cubicle housing systems equipped with slatted (25 g day^{-1} per cow) and V-shaped floors (26-45 g day^{-1} per cow) are considered (Table 2.1). Besides the small number of data present for the comparison, experimental conditions during the measurements reported in Table 2.2 were different. Slatted floor research was carried out in different countries, in different seasons and under different management conditions, whereas data used for the direct comparison (Table 2.2) were obtained from an experiment with both floor types under comparable experimental conditions. Braam *et al.* (1997) and Braam & Van den Hoorn (1996) concluded that the design of solid floors and in particular the design and area of openings are important features when it comes to reduction of air exchange and maximisation of emission reduction. In the evaluation of the emission reducing effect of housing systems with V-shaped solid floor, compared to slatted floors, the volume of urine left upon the floor surface after each urination needs to be considered too. Urine volume and urea concentration both determine the amount of urea upon the floor and thus also the potential NH_3 production in and emission from the urine puddles upon the floor. Braam & Van den Hoorn (1996) reported typical values for both parameters are 0.6 mm and 0.8 m^2 respectively for clean slatted floors, while for V-shaped (3% slope) solid floors due to draining of urine typical values are 0.15 mm and 1.2 m^2 respectively. This means that the potential NH_3 emission for a slatted floor is on average three times higher than for a V-shaped solid floor. Both the reduced potential emission and the reduced air exchange when using solid floors may contribute to the emission reduction reported. A major point of attention when using solid floors in general and inclined solid floors in particular is locomotion of the animals. On an inclined surface cows can easily loose grip which may cause slip incidents and injuries, especially when faeces are not removed thoroughly. Floors with sufficient floor surface texture and roughness may improve that situation (Dumelow & Albutt, 1988). Furthermore, Braam *et al.* (1997b) showed that regular wetting of the floor surface could improve faeces removal and reduce the problems mentioned before.

7 Synthesis

Assuming NH_3 in dairy cow buildings only originates from urinary urea and 80% of urinary N is in the form or urea, potential daily NH_3 emission per cow is 65-260 g (80% of 80-320 g N excreted in urine per cow and per day). Measurements (Table 2.1) have shown that the actual daily NH_3 emission is in the order of magnitude of 30 g per day, which is 12-46% of the potential emission. The lower percentage is assumed to be relevant for intensive dairy farming and related high levels of N input. An important reason for the large difference between actual and potential emission is that at pH values for urine and slurry, on average 8.5 and 7.5 respectively, only a relatively small percentage of TAN is present in the form of volatile, unionised NH_3. Even at reported pH levels of around 8.6 for urine on the floor and the top layer of slurry in the pit (Elzing & Monteny, 1997a), much of the TAN will be present as non-volatile NH_4^+. Beside pH, also other emission determining parameters have to be considered to fully explain the low actual emission relative to the potential emission. Elzing & Monteny (1997a, 1997b) found that the mass transfer parameters air velocity and temperature highly determine the maximum volatilisation rate per urination, occurring at approximately 2 h after urine has been deposited on the floor, as well as the duration of the volatilisation process (up to 15 h or more). At air velocities, temperatures and emitting surface areas found in diary cow buildings, NH_3 losses due to mass transfer (volatilisation) will be at a relatively low level when compared to NH_3 production in the liquid following urea hydrolysis. Furthermore, each urine pool upon the floor will be refreshed within 10 h at an average urination frequency per cow of 11 day^{-1} (Whitehead, 1995), a floor area of 0.8 m^2 covered by one urination, an available floor area per cow of 3.5 m^2 and random distribution of urinations over the available floor area (Monteny *et al.*, 1998). The volatilisation process of the original urine pool will therefor never run to completion.

Agricultural NH_3 emission originates for 53% and 60% from cattle husbandry in Europe and The Netherlands, respectively (Asman, 1995; Anonymous, 1996). Pig and poultry husbandry is responsible for the remainder. When Dutch emission reduction goals (70% in 2005 relative to 1980) would be applied on a European scale, NH_3 emissions from all sources (land spreading slurry, buildings, storages, grazing) would have to be substantially reduced to achieve them.

New techniques for slurry application and covering of outside slurry storages are already law enforced in The Netherlands since the late 80's. They are applied on a large scale nowadays. As a consequence, the national NH_3 emission reduction was calculated to be approximately 69 kton (34%) in 1995 compared to 1980 (Anonymous, 1996). The contribution of cattle housing and storage systems to the total NH_3 emission in The Netherlands was estimated at 45 kton in 1995 (Anonymous, 1996). Based upon the number of dairy cows relative to the number of other cattle (Anonymous, 1995), it can be assumed that approximately 80% (36 kton per year) of this amount originates from dairy cow buildings. Data presented in Table 2.2 show that an NH_3 emission reduction of 50% seems technically feasible. This can be achieved through innovative floor systems, flushing with diluted formaldehyde, and through a combination of feeding strategies and e.g. flushing with water.

Emission reduction in building generally lead to an increase in the nitrogen content of the slurry. This might imply an additional NH_3 emission during storage and land spreading is to be expected. However, when measures are taken to reduce these emissions substantially (covering of storages, low emission land application), the additional emission will be low. Assuming 100% penetration of these measures in practice, maximal reduction of the NH_3 emission on a national scale will be 18 kton. This means that the contribution from dairy cow buildings to achieve the government goal in 2005, an additional reduction of 74 kton from 1995 onward (total reduction of 143 kton per year), will be small and a further emission reduction from all agricultural sources will be necessary. Furthermore, annual costs on farm scale of these NH_3 emission reducing measures might be significant (Van Scheppingen *et al.*, 1995), although real figures from practice are few.

8 Conclusions

Accurate measurement of ventilation rates for naturally ventilated animal buildings has become feasible using tracer gas mass balance methods.

Data on the NH_3 emission from different types of dairy cow housing systems indicate that variation is large and that emission from tie stalls (5-27 g day^{-1} per cow) is generally lower than from loose housing systems (20-45 g day^{-1} per cow). Urea concentration in the urine, urease activity, pH, temperature, air velocity and area of emitting surfaces (floor, pit) are influencing parameters for the emission of NH_3. Measures to reduce NH_3 emission from diary cow buildings affect one or more of these parameters. Most effective measures are flushing with formaldehyde (reduction of urease activity), introduction of V-shaped, solid floors (minimising air exchange between pit and building, and reduction of air velocity in the pit), feeding strategies (lowering or urea concentration in the urine) and slurry acidification (pH control). Drawbacks of these measures, like the possible volatilisation of formaldehyde gas when flushing floors with diluted formaldehyde, danger of slipping of the cows on V-shaped, solid floors and risks of unwanted emissions of methane (straw systems) and nitrous oxide (acidification) will have to be addressed to ensure application in practice. For the Netherlands, maximal emission reduction through implementation of reducing measures in dairy cow buildings is estimated at 18 kton of NH_3 per year.

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3

A conceptual mechanistic model for the ammonia emissions from free stall cubicle dairy cow houses

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Abstract

A conceptual model, consisting of floor and slurry pit modules, for estimating ammonia emission from cubicle (free stall) dairy cow houses was developed. Components in the floor module described urine deposition, enzymatic conversion of urea, dissociation of ammonia and ammonia volatilization. Slurry pit module components described urine and feces production, and ammonia dissociation and volatilization.

Validity of the model was tested by comparing results on a monthly basis with measurements of ammonia emissions from January to June for a commercially-operated, mechanically-ventilated research cow house. Maximal underestimation was 6% for May and maximal overestimation was 7% for March. A sensitivity analysis was carried out on the input parameters for which measured data were unavailable. This analysis showed that urease activity had little effect on the simulated emission and the largest effect was due to pH. The reliability of the model for predicting the ammonia emission for practical conditions will mainly depend on the validity of assumptions concerning the time independent character of most of the parameters and on the accuracy with which parameters can be determined.

Keywords: ammonia volatilization, computer simulation, dairy cows, sensitivity analysis

1 Introduction

In regions with high livestock densities, ammonia (NH_3) plays an important role in environmental acidification. In the Netherlands 46% of the acidification of forest, heath lands and sweet water ecosystems is caused by the deposition of NH_3, mainly originating from agricultural activities (Heij and Schneider, 1995). Dutch governmental policy concerning environmental acidification aims to reduce NH_3 emissions by 70% in the next decade (Anonymous, 1993). This reduction is relative to the national emission level in 1980, when 240,000 tons of NH_3 were emitted (Oudendag, 1993). Technical measures to reduce NH_3 emissions after slurry application and during slurry storage are already enforced by law in the Netherlands (Voorburg, 1991; Berentsen *et al.*, 1992). Reduction of NH_3 emission from animal housing systems is necessary to comply with long term national reduction goals (Anonymous, 1993). To achieve this, the impact of changes in the composition of diets leading to a lower excretion of nitrogen, and technical solutions involving advanced slurry handling and innovative floor and housing systems are being studied.

Approximately 90% of dairy cows in the Netherlands are kept in naturally ventilated houses equipped with cubicles (free stall), slatted floors and facilities for long term slurry storage under the slats and the cubicles. Measurements of the NH_3 emission from naturally ventilated houses are technically complex, expensive and labour intensive. This is primarily due to difficulties in determining the ventilation rate. NH_3 emission related processes are also complex. Modeling of the processes related to the production and emission of NH_3 may improve insight into this complexity. Also, NH_3 emission levels and their potential reduction by technical and nutritional measures can be predicted without the uncertainty of ventilation rate measurements mentioned above. Furthermore, simulation offers the potential to study the effect on NH_3 emission of single and combined solutions and to optimize them in a cost effective manner.

Muck and Steenhuis (1981) reported an analytical model for quantifying the loss of nitrogen due to NH_3 volatilization from urine applied upon the surface of an alley in a commercial, free stall dairy barn. They concluded that their model insufficiently characterized the conversion of urea in the urine directly after urine application and that nitrogen loss through NH_3 volatilization was underestimated for cool conditions. Elzing *et al.* (1992) and Elzing and Monteny (1997) described a model for the simulation of NH_3 emission after application of a mixture of feces and urine and only urine on a slatted floor element in a scale model of a dairy cow house. They concluded that urea conversion and NH_3 volatilization from the floor element could be modeled successfully if urea conversion rates were assumed to be much higher than those obtained from laboratory analysis of fresh slurry and by assuming complete mixing of urine upon the floor.

Neither the Muck and Steenhuis (1981), the Elzing *et al.* (1992) nor the Elzing and Monteny (1997) models were directly suitable for simulating the NH_3 emission from a dairy cow house. Following conclusions from the work by Elzing and Monteny (1997), the model NH_3 emission after urine application on a slatted floor element was used as a basic component for the current dairy cow house model. A procedure for simulation of urination behavior and a module for the NH_3 emission from the slurry pit were developed and integrated to complete the conceptual model for a free stall cubicle dairy cow house.

Objectives

The objective of this paper is to describe the development and validation of a conceptual model for the emission of NH_3 from free stall dairy cow houses with cubicles, slatted floors and slurry storage in a pit under the slats and cubicles. Modules describing NH_3 emission from the slatted floors and the slurry pit are intended to accurately predict emission levels on a monthly basis. The use of models is cheaper than measurements of NH_3 emissions and allows more rapid comparison of slurry handling and management strategies. To ensure a realistic outcome, the model uses measured parameters and field data to the extent possible. Finally, a sensitivity analysis is performed.

2 Model description and theory

2.1 Model description

In the Netherlands, most of the dairy cows are housed in free stall dairy cow houses with cubicles, slatted floors and slurry storage under slats and cubicles. In these houses, referred to as cubicle houses, animals urinate and defecate upon the slatted floor. A small part of the urine remains on the floor surface. The main part of the deposited urine flows through the slats to the slurry pit. Feces fall through the slats, mainly under influence of animal locomotion and gravity. Figure 3.1 gives a schematic representation of the components of the floor and slurry pit modules that comprise the model.

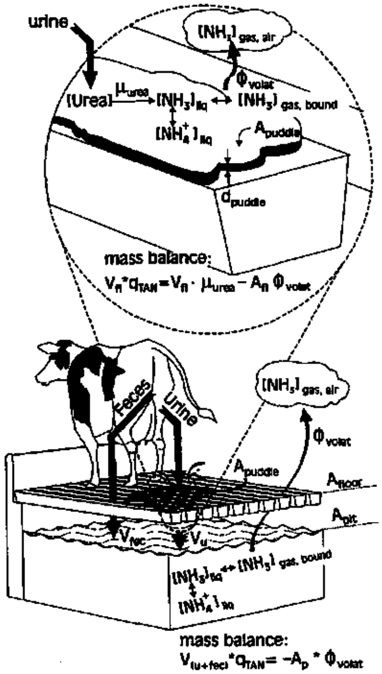

Figure 3.1: Schematic representation of the ammonia emission model for cubicle dairy cow houses.

Modules and components

The basic component in the floor module is a urine puddle that remains on the slatted floor after each urination (Elzing and Monteny, 1997). NH_3 originates mainly from the enzymatic conversion of urea, present in the urine (Muck and Steenhuis, 1981). Ammonium (NH_4^+) in the urine is in equilibrium with NH_3 (dissociation equilibrium). NH_3 in the urine and at the puddle/air boundary is in equilibrium according to Henry's law, and is transported across the liquid/air interface to the air inside the building (convective mass transfer or volatilization). These processes form the components of the floor module.

For the slurry pit module, excreted urine and feces mix instantly with the stored slurry. Hence, the basic element of the slurry pit module is the total volume of slurry in the pit. The urea that flows to the slurry pit after each urination is diluted in a homogenous mix of feces and urine, and then converted into a constant concentration of total ammonia (NH_3 and NH_4^+) in the slurry. This concentration depends on initial urea concentration, volumes of feces and urine produced, and volatilization.

Ammoniacal nitrogen mass balance

A mass balance for total ammoniacal nitrogen (TAN; sum of ammonia nitrogen (NH_3-N) and ammonium nitrogen (NH_4^+-N)) in a urine puddle and in the slurry pit is the basis for mathematical description of the components in the floor and the slurry pit module. For a single urine puddle, this balance is:

$$V_{fl} * q^{*}_{TAN} = V_{fl} * \mu_{urea} - A_{fl} * \Phi''_{volat} \qquad [3.1a]$$

and for the accumulated urine and feces in the slurry pit:

$$V_{(u+fec)} * q^{*}_{TAN} = - A_p * \Phi''_{volat} \qquad [3.1b]$$

with:

V_{fl} = volume of the urine puddle on the slatted floor (m^3)
q^{*}_{TAN} = rate of accumulation of TAN per unit of volume ($kg\ m^{-3}\ s^{-1}$)
A_{fl} = slatted floor area covered by a puddle (m^2)
Φ''_{volat} = NH_3-N mass flux due to volatilization ($kg\ m^{-2}\ s^{-1}$)
μ_{urea} = rate of NH_3-N production through enzymatic conversion of urea nitrogen ($kg\ m^{-3}\ s^{-1}$)
$V_{(u+fec)}$ = volume of urine and feces in the slurry pit (m^3)
A_p = area of the slurry pit (m^2)

In the floor module (Equation 3.1a), the left hand side represents the net rate of change in the TAN-concentration ([TAN]) in the puddle due to the right hand side terms: the production of NH_3-N following urea nitrogen conversion ($V_{fl}*\mu_{urea}$) and the loss due to volatilization of NH_3-N ($-A_{fl}*\Phi''_{volat}$). In the slurry pit module, this change is only due to volatilization (Equation 3.1b).

Volumes of urine and feces

For the floor module, the volume of a single urine puddle on the floor is:

$$V_{fl} = A_{fl} * d_{fl} \quad [3.2]$$

with:

d_{fl} = thickness of the urine puddle on the slats (m)

The volume of the slurry in the slurry pit is calculated as follows:

$$V_{(u+fec)} = n_c * n_{days} * (V_{fec} + V_u) \quad [3.3]$$

with:

n_c = number of cows (dimensionless)
n_{days} = number of days after start of simulation (dimensionless)
V_{fec} = volume of feces produced ($m^3\ cow^{-1}\ day^{-1}$)
V_u = volume of urine produced ($m^3\ cow^{-1}\ day^{-1}$)

In Equation 3.3, the volume of the urine puddle on the floor is assumed to be small compared to the volume of feces and urine produced and is therefore ignored.

Urination behavior

To simulate urination behavior of the animals, distribution of urinations over the available locations for urine deposition is modeled probablistically as a Poisson process. The time interval between successive urinations is exponentially distributed around the total number of urinations, determined by multiplying the urination frequency (u_f; $cow^{-1}day^{-1}$) and the number of cows (n_c); see Table 3.1. The number of locations available for urine deposition is determined by the available slatted floor area of the house (A_{house}) divided by the floor area covered by one urine puddle (A_{fl}). Emission from the sides and bottom of slats was ignored, so the floor area relevant for the emission is the area on top of the slats.

2.2 Theory

Enzymatic conversion

Urea is converted to NH_3 in a reaction that is catalyzed by the enzyme urease. Urease is produced by micro organisms present in feces. Bacterial activity was mainly found in a persistent, thin solid layer upon floor surfaces (Ketelaars and Rap, 1994; Elzing and Monteny, 1997). Therefore, in the floor module, urea conversion is modeled as a Michaelis-Menten differential equation, characterizing enzymatic processes where the amount of substrate limits the conversion process at low concentrations:

$$\mu_{urea} = \frac{\mu_{max}\,[U_t]}{K + [U_t]} \quad [3.4]$$

with:

μ_{max} = maximal rate of urea nitrogen conversion at high concentrations ($kg\ m^{-3}\ s^{-1}$)
$[U_t]$ = concentration of urea nitrogen in the urine at time t ($kg\ m^{-3}$)
K = Michaelis-Menten constant for urea conversion ($kg\ m^{-3}$)

The parameter μ_{max} is often referred to as urease activity. At t = 0, $[U_t]$ equals initial urea nitrogen concentration in the urine produced ($[U_o]$).

Dissociation

The produced NH_3 will dissociate in the liquid and the resultant concentrations of NH_3 and NH_4^+ will maintain equilibrium, depending on temperature and pH. The fraction of NH_3-N (f), expressed as the quotient of the concentrations of NH_3-N and NH_4^+-N, is:

$$f = \frac{[NH_3-N]_{liq}}{[NH_3-N]_{liq} + [NH_4^+-N]_{liq}} = \frac{1}{1 + \frac{[H^+]}{K_a\, 1.07^{(T-293)}}} \qquad [3.5]$$

with:

f = fraction of NH_3-N (dimensionless)

$[NH_3\text{-}N]_{liq}$ = *concentration of NH_3-N in the liquid* (kg m^{-3})

$[NH_4^+\text{-}N]_{liq}$ = concentration of NH_4^+-N in the liquid (kg m^{-3})

$[H^+]$ = concentration of hydrogen ions in the liquid (10^{-pH}; kg m^{-3})

K_a = adapted acid dissociation constant for NH_3 (dimensionless)

T = absolute temperature (K)

As in Hashimoto and Ludington (1972), K_a is assumed to be temperature independent and equal to $0.81*10^{-10}$.

Convective mass transfer

Loss of NH_3-N from the liquid to the air takes place through convective mass transfer (volatilization). Its magnitude depends on the mass transfer coefficient and the difference between gaseous NH_3-N concentration at the boundary between the emitting surfaces (puddle on slats and top layer of slurry pit) and the air inside the house:

$$\Phi''_{volat} = k\,([NH_3\text{-}N]_{gas,\,bound} - [NH_3\text{-}N]_{gas,\,air}) \qquad [3.6]$$

with:

k = mass transfer coefficient for NH_3 (m s^{-1})

$[NH_3\text{-}N]_{gas,\,bound}$ = concentration of gaseous NH_3-N at the boundary (kg m^{-3})

$NH_3\text{-}N]_{gas,\,air}$ = concentration of gaseous NH_3-N in the air (kg m^{-3})

The mass flux is related to the area covered by each urine puddle (A_{fl}) in the floor module and to the slurry pit area (A_p) exposed to atmospheric conditions in the slurry pit module.
The volatilization process is essentially mass transfer of NH_3 through a liquid/gas boundary at the emitting surfaces, assuming well mixed liquid and gas phases (Haslam *et al.*, 1924). They empirically found the - partial pressure based - mass transfer coefficient to be dependent on the molar mass of NH_3, air velocity and air temperature. Using the ideal gas law at a temperature of 283 K (see: Elzing and Monteny, 1997) for example, the concentration based mass transfer coefficient is:

$$k = 48.4\ v^{0.8}\ T^{-1.4} \qquad [3.7]$$

with:

v = air velocity ($m\ s^{-1}$)

The concentration of NH_3-N in the liquid is in equilibrium with the concentration in the gas phase at the boundary between the puddle or slurry pit top layer (liquid) and the air according to Henry's law:

$$\frac{[NH_3 - N]_{liq,\ bound}}{[NH_3 - N]_{gas,\ bound}} = H \qquad [3.8]$$

with:

$[NH_3\text{-}N]_{liq,\ bound}$ = concentration of NH_3-N in the liquid at the boundary (=$[NH_3\text{-}N]_{liq}$; see Equation 3.5; $kg\ m^{-3}$)

H = Henry's constant (dimensionless)

Henry's constant is temperature dependent and can be expressed as (Hashimoto and Ludington, 1971):

$$H = 1.384\ 10^3 * 1.053^{(293-T)} \qquad [3.9]$$

2.3 The model

Substitution for the terms in Equation 3.1a with the terms in Equations 3.2, 3.4 and 3.6 results in a mass balance equation (3.10a) for the urine puddle. $[NH_3\text{-}N]_{gas,\ air}$ in Equation 3.6 is assumed to be zero in this substitution. For the floor module, the model calculates values of f (Equation 3.5), k (Equation 3.7) and H (Equation 3.9) as a function of temperature and air velocity. In equation 3.10a, the subscript "fl " is added to the parameters to indicate "floor module".

$$(A_{fl} * d_{fl}) \frac{d([NH_3 - N]_{liq,\ fl} + [NH_4^+ - N]_{liq,\ fl})}{dt} = (A_{fl} * d_{fl})\ \frac{\mu_{max}\ [U_t]}{K + [U_t]} - k_{fl}\ A_{fl} \frac{f_{fl}\ ([NH_3 - N]_{liq,\ fl} + [NH_4^+ - N]_{liq,\ fl})}{H_{fl}} \qquad [3.10a]$$

This equation is valid for each urine puddle. Processes start directly after urine deposition and are assumed to continue until a new urination covers the present urine puddle. The old puddle is then flushed to the slurry pit and the processes for the new puddle start.

Substituting Equations 3.3 and 3.6 in Equation 3.1b results in the TAN mass balance for the slurry pit module (Equation 3.10b), assuming $[NH_3\text{-}N]_{gas,\ air}$ equals zero. As in the floor module, f, k and H are calculated by the model using Equations 3.5, 3.7 and 3.9 respectively, where subscript "p" refers to the slurry pit module:

$$V_{(u\ +\ fec)} \frac{d([NH_3 - N]_{liq,\ p} + [NH_4^+ - N]_{liq,\ p})}{dt} = - k_p\ A_p \frac{f_p\ ([NH_3 - N]_{liq,\ p} + [NH_4^+ - N]_{liq,\ p})}{H_p} \qquad [3.10b]$$

[TAN] in a urine puddle and in the slurry pit at a certain time t is calculated by solving Equations 10a and 10b, respectively. NH_3-N emission from the cow house is calculated by adding values of the second term of the right hand side of Equation 10a for all urine puddles and the right hand side of Equation 10b. Cumulative NH_3 emission, where NH_3 emission is 17/14 times the emission of NH_3-N, is calculated by adding the integral of both terms using time steps of 1 minute. The model is written in PERSONAL PROSIM (Sierenberg and De Gans, 1993), running on a PC.

3 Simulation: model initialization, results and discussion

Simulation was carried out for the cubicle dairy cow house described by Kroodsma *et al.* (1993). The house with 40 lactating dairy cows was used to measure NH_3 emission from January to June 1989. It was mechanically ventilated to enable emission measurements. Data on NH_3 emission and inside air temperature, to perform model calculations and to compare calculations with measured emissions, were available as averages on an hourly and a monthly basis.

3.1 Model initialization: inputs to the model

Input parameters for the model follow from the model description and the theory described in the previous paragraphs. They are summarized in Table 3.1.

No data were found in literature about the area covered by a urination on a slatted floor (A_{fl}). A value of 0.8 m^2 is assumed, based upon unpublished results by Ketelaars *et al.* (1995). Elzing and Monteny (1997) calculated a thickness for a urine film (d_{fl}) of 0.48 mm for a slatted floor in experiments in a scale model system. Both values are taken as a fixed input for the model.

The average daily slurry production (V_u+V_{fec}) of high producing dairy cows during the housing period, including water for cleaning of the milking parlor that is stored in the slurry pit, is approximately 60 kg per cow (Anonymous, 1994) and the urine to feces mass ratio (V_u/V_{fec}) is 2:3 (Morse *et al.*, 1994). Bulk densities for urine and feces are assumed to be equal to that for water (1,000 kg m^{-3}). Hence, the volume based urine to feces production ratio is also 2:3 and the daily production per cow of urine (V_u) and feces (V_{fec}) is 0.024 and 0.036 m^3, respectively.

Inputs to the urea conversion process are the actual urea nitrogen concentration of the urine ($[U_t]$), the maximal rate of urea nitrogen conversion (μ_{max}) and Michaelis' constant (K).

Table 3.1: Summary of parameter values per model component.

Component	Value in module of		Equation	Reference
parameter (unit)	floor	slurry pit		
Urine and feces production				
A_{fl} (m^2)	0.8		(3.2)	*
d_{fl} (m)	0.0005		(3.2)	*
n_c (dimensionless)	40		(3.3)	Kroodsma *et al.*, 1993
V_u (m^3 cow^{-1} day^{-1})	0.024		(3.3, 3.11)	*
V_{fec} (m^3 cow^{-1} day^{-1})	0.036		(3.3, 3.11)	*
V_u/V_{fec} (dimensionless)	2:3		(3.11)	Morse *et al.*, 1994
$[U_0]$ (kg m^{-3})	7.65		(3.11)	*
Urination behavior				
u_f (day^{-1} cow^{-1})	10			Hafez, 1969
n_c (dimensionless)	40			Kroodsma *et al.*, 1993
A_{fl} (m^2)	0.8			*
A_{house} (m^2)	140			Kroodsma *et al.*, 1993
Enzymatic conversion				
$[U_t]$ (kg m^{-3})	$=[U_0]$ at $t = 0$		(3.4)	*
μ_{max} (kg m^{-3} s^{-1})	$2.70*10^{-3}$		(3.4)	*
K (kg m^{-3})	$56*10^{-3}$		(3.4)	Elzing *et al.*, 1992
Dissociation				
T (K)	T_{air}	T_{air}	(3.5)	Kroodsma *et al.*, 1993
pH (dimensionless)	8.6	8.6	(3.5)	Elzing *et al.*, 1992
Convective mass transfer				
T (K)	T_{air}	T_{air}	(3.7)	Kroodsma *et al.*, 1993
v (m/s)	v_{fl}: Eqn. 3.12	10% of v_{fl}	(3.7)	*
A_{fl} (m^2 $puddle^{-1}$)	0.8		(3.10a)	*
A_p (m^2)		184	(3.10b)	Kroodsma *et al.*, 1993

* = calculated or estimated

The initial value of $[U_t]$, being $[U_0]$, depends on animal and diet related factors. For this study, no measured data were present. The initial concentration of TAN in the slurry pit, reported by Kroodsma *et al.* (1993), and the slurry to urine production ratio were used to calculate $[U_0]$:

$$[U_0] = ([NH_3\text{-}N]_{liq,\,p}+[NH_4^+\text{-}N]_{liq,\,p}) * ((V_u+V_{fec})/V_u) \qquad [3.11]$$

with:

$[U_0]$ = initial concentration of urea nitrogen in the urine produced (kg m^{-3})

Using this equation and a TAN concentration of the slurry of 3.06 kg m^{-3} (Kroodsma *et al.* 1993), $[U_0]$ would have been 7.65 kg m^{-3} (3.06 * 5/2).

Values for K and μ_{max} have to be determined through laboratory analysis. Elzing *et al.* (1992) found a value for K of 56 10^{-3} kg of urea nitrogen per m^3 or per 1,000 kg for a mixture of urine and feces, which is taken as a fixed input for the model. They also reported values for μ_{max} of 0.08 10^{-3} kg of urea nitrogen m^{-3} s^{-1} for a mixture of fresh urine and feces and of 0.58 10^{-3} kg of urea nitrogen m^{-3} s^{-1} for a urine/feces mixture upon a slatted floor in scale model experiments. Ketelaars and Rap (1994) found much higher values in specific trials in an experimental dairy cow house. Combining findings by Elzing *et al.* and Ketelaars and Rap, μ_{max} is assumed to be 2.7 10^{-3} kg m^{-3} s^{-1}. In modelling K and μ_{max}, no influence of temperature is assumed for the temperature range in this study.

The dissociation process has temperature and pH as inputs. The floor surface and slurry pit surface are assumed to have the same temperature as the inside air. Values are taken from Kroodsma *et al.* (1993). Elzing *et al.* (1992) reported pH values at the top layer of the slurry pit of 8.6 in experiments in a scale model system. This pH was quite independent of experimental conditions and origin and composition of the urine. Their value is used in this study.

Temperature of the emitting surfaces and air velocity determine the convective mass transfer coefficient. Both surface temperature and air velocity will vary strongly in practice, depending on building characteristics (ventilation system), floor structure (slatted floors, solid floors) and animal related parameters (movement, position). Muck and Steenhuis (1981) measured air velocities ranging from 0.05 to 0.30 m s^{-1} and air temperatures ranging from 5 to 25 °C in the naturally ventilated cow house used for their experiments. Although no relationship between air velocity and air temperature was reported and no air velocities were reported by Kroodsma *et al.* (1993), the following equation, derived from the limited data of Muck and Steenhuis (1981), was used in this study to relate inside air temperature and air velocity at floor level:

$$v_{fl} = 0.05 + 0.0125\,(T_{air} - 278) \qquad [3.12]$$

with:

v_{fl} = air velocity at floor level (m s^{-1})

T_{air} = inside air temperature (K; where $T > 278$)

The result of this equation seems reasonable for the cubicle house in this study, because the ventilation rate was linearly dependent on inside air temperature (Kroodsma *et al.*, 1993). Air velocity at slurry level in the pit is assumed to be 10% of the air velocity at floor level, although no data were present to support this assumption.

Little is known about the urination frequency of cows. Based upon data reported by Hafez (1969) for high producing, lactating dairy cows a urination frequency (u_f) of 10 cow^{-1} day^{-1} is assumed. For the cubicle house under study, the slatted floor area (A_{house}) was 140 m^2 (3.5 m^2 per cow) and the area of the slurry pit (A_p) was 184 m^2 (Kroodsma *et al.*, 1993).

3.2 Simulation results

For the cubicle house used in this study, the animals were inside day and night from 1 January to 17 May. The ration consisted of grass and maize silage (65%/35% based upon dry matter) and additional concentrates depending on the individual milk production level. During the rest of May and all of June, the cows were kept inside between 16:00 and 07:00 h and grazed during the rest of the day. When inside the house during those months, the cows were allowed to consume concentrates related to the individual milk yield and 3-4 kg dry matter day^{-1} of maize silage.

Comparison of measured monthly NH_3 emissions (Kroodsma *et al.*, 1993) and simulated monthly NH_3 emission is shown in Table 3.2. Monthly average inside air temperatures were taken from Kroodsma *et al.* (1993). These values were also used to calculate local air velocities (Equation 3.12 and Table 3.1). Other parameters were as in Table 3.1. For May, the simulated emission is calculated as a weighted mean of runs for non-grazing and partly grazing periods of 17 and 14 days, respectively.

Table 3.2: Measured temperature (^oC) and measured and simulated mean NH_3 emission (kg cow^{-1} month^{-1}) for a cubicle house with 40 lactating cows.

		NH_3 emission			
Month	Temperature	measured	simulated	difference	(%)
January	11.8	0.963	0.959	0.004 (-/-)	0
February	12.4	0.965	0.983	0.018	2
March	14.4	1.095	1.174	0.079	7
April	14.1	1.095	1.121	0.026	2
May	18.4	1.505	1.420	0.085 (-/-)	- 6
June	18.2	1.170	1.238	0.068	6
Total		6.793	6.895	0.102	3.8

Total difference between model calculations and measured values for the total period was 102 g NH_3 cow^{-1}. On a monthly basis, maximal underestimation was 6% in May and maximal overestimation was 7% in March. The absolute value of the average monthly error term was 3.8%.

Daily patterns of calculated and measured NH_3 emission for periods with and without grazing during daytime are given in Figure 3.2 (from 1 May 12:00 h to 5 May 12:00 h) and Figure 3.3 (from 26 May 12:00 h to 30 May 12:00 h), respectively. Hourly average inside air temperatures, and thus hourly calculated air velocities (Equation 3.12), were used as input. Values of all other parameters were kept at values given in Table 3.1.

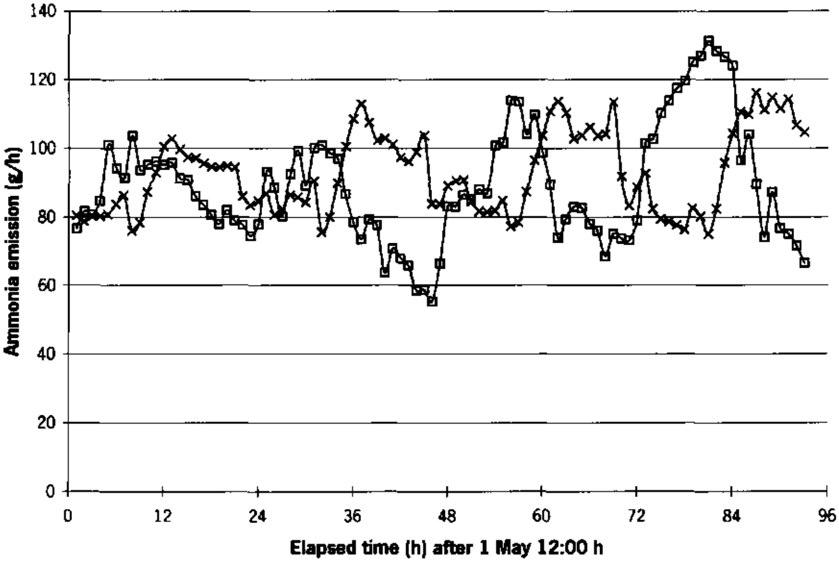

Figure 3.2: Measured (xxx) *and calculated* (□□□) *ammonia emission during 4 days in May with animals permanently inside.*

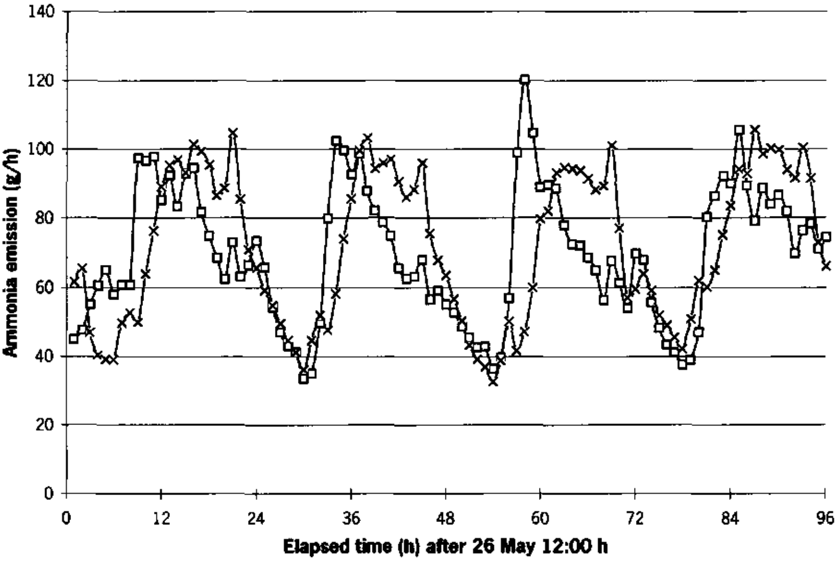

Figure 3.3: Measured (xxx) *and calculated* (□□□) *ammonia emission during 4 days in May with animals grazing during daytime.*

For the period when the animals were kept inside the house, average measured and calculated NH_3 emissions are in the same order of magnitude, because underestimations and overestimations are more or less compensated. From the limited input data available, no reasonable explanation could be found for this discrepancy in dynamics.

Model predictions show good accordance with measurements for the period with part time grazing (Figure 3.3). Highest levels during night time (emission from floor and slurry pit) and lowest levels during the day (emission from slurry pit) match well. This indicates that the input parameters for the floor and slurry pit modules are reliable. Dynamics of the measured and calculated NH_3 emission match very well too. Both the decay of emission, occurring when the animals leave the house (around 07:00 h) and no urination takes place, and the increasing emission after the animals re-enter the house (at approximately 16:00 h) are simulated satisfactorily.

3.3 Sensitivity analysis

To assess possible explanations for the differences between modeled and measured NH_3 emissions, a sensitivity analysis was carried out for parameters that were heavily based on assumptions. They are:

- urination frequency;
- thickness of the urine puddle;
- area per urine puddle;
- air velocity;
- temperature;
- pH;
- urease activity.

Except for the parameter under study, all others were kept at values given in Table 3.1. To separate the effect of temperature and air velocity (Equation 3.12), air velocity at floor level was kept at 0.17 $m\ s^{-1}$ (0.017 $m\ s^{-1}$ for the slurry pit) in the sensitivity analysis of all other parameters.

All parameters mentioned above influence the NH_3 emission from the floor, whereas temperature, air velocity and pH are only relevant for the slurry pit module.

The effects of urination frequency, air velocity, temperature and urease activity are shown in Figures 3.4 through 3.7.

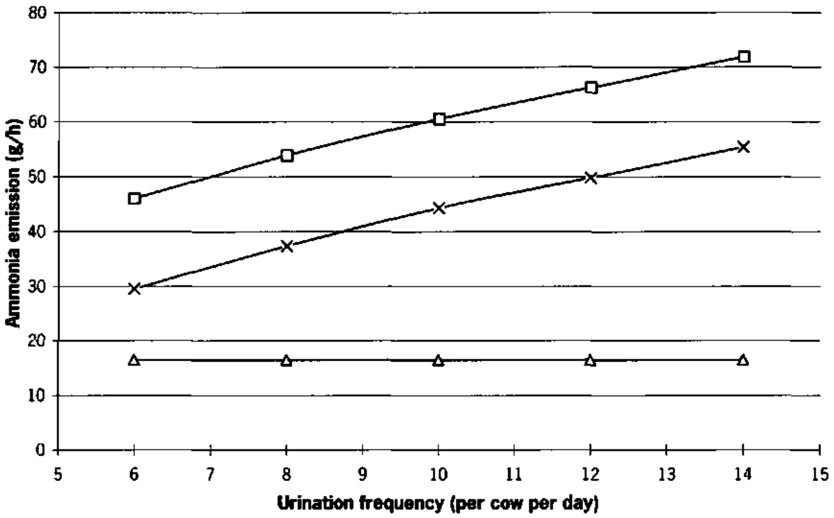

Figure 3.4: Calculated ammonia emission from slurry pit (ΔΔΔ), floor (xxx) and cow house (□□□) as a function of urination frequency.

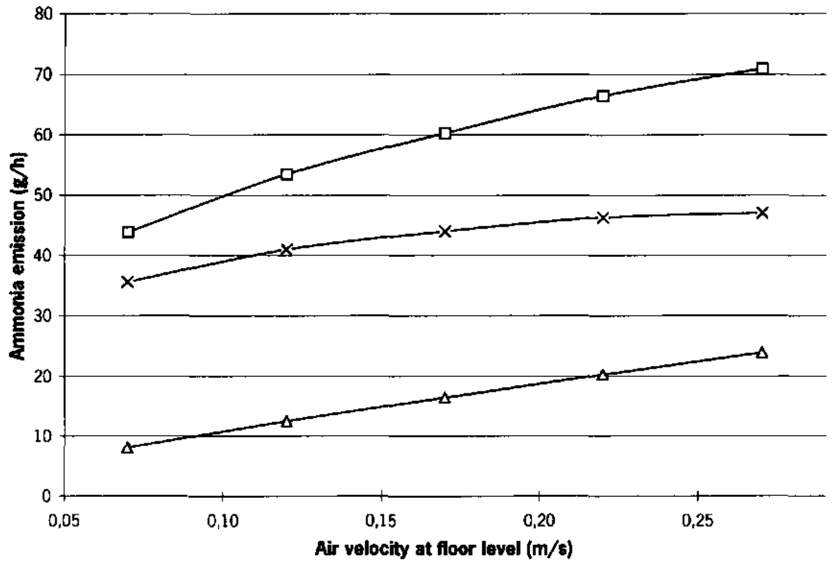

Figure 3.5: Calculated ammonia emission from slurry pit (ΔΔΔ), floor (xxx) and cow house (□□□) as a function of air velocity at floor level (and thus at slurry level).

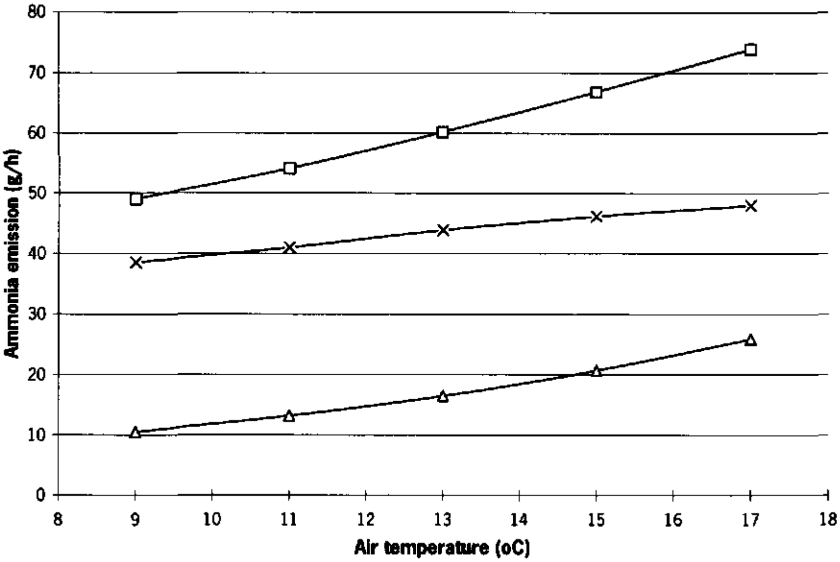

Figure 3.6: Calculated ammonia emission from slurry pit (ΔΔΔ), floor (xxx) and cow house (□□□) as a function of air temperature.

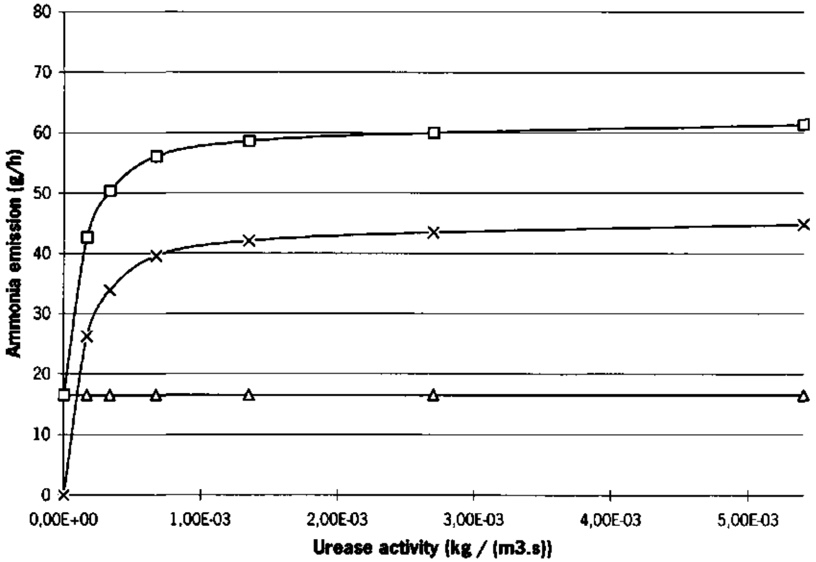

Figure 3.7: Calculated ammonia emission from slurry pit (ΔΔΔ), floor (xxx) and cow house (□□□) as a function of urease activity.

The relationship between NH_3 emission and urination frequency is close to linear. When urination frequency increases, the floor is wetted more intensively. Per time unit more urea nitrogen is present upon the floor, leading to a higher production and emission of NH_3. A decreasing effect may be expected for higher urination frequencies, because chances increase of old puddles being replaced by a fresh one at an early stage of their emission process.

The non-linear impact of air velocity on the NH_3 emission from the floor is related the power of 0.8 for air velocity used in the equation for mass transfer of NH_3 (Equation 3.7). For the slurry pit, the relationship seems linear, but this is because air velocity at slurry level, being 10% of the air velocity at floor level, only varied from 0.007 - 0.027 m/s in this analysis.

Air temperature influences dissociation and convective mass transfer. The overall impact on NH_3 emission seems linear for the floor, whereas for the slurry pit an exponential relationship is evident.

Urease activity hardly influences NH_3 emission. Except at very low values, valid for new floors (Elzing and Monteny, 1997), the potential for urea conversion does not appear to limit the NH_3 emission process.

For thickness and area of a urine puddle on the floor, the relationship with NH_3 emission is linear and exactly the same on a relative scale. This is due to similar effects of both parameters on the volume of urine and the amount of urea present in the puddle. An increase of the thickness or the area of a urine puddle by 50% (from 0.48 to 0.72 mm or from 0.8 to 1.2 m^2 respectively) leads to approximately 25% higher NH_3 emissions.

Sensitivity of the model for pH is very pronounced. A reduction of pH from 8.6 to 7.1 leads to a 90% reduction of NH_3 emission. This effect follows from the fundamental relationship between pH and the fraction of NH_3-N in the liquid (Equation 3.5).

4 Discussion

Simulated and measured monthly emission levels, their total for the six months period (Table 3.2) and daily patterns, especially for the period with part time grazing, showed good agreement for the cow house in this study, even though values of only a few parameters could be taken directly from Kroodsma *et al.* (1993). Validity of the model for prediction of NH_3 emission levels from a single urine puddle applied on a slatted floor element, investigated in a scale model system of a dairy cow house, was already shown by Elzing and Monteny (1997). The results from the present study show that extension of that model with a procedure for urination behavior and a module for the slurry pit emission represents the situation in a cubicle dairy cow house reasonably well. Agreement between simulation and measurements indicates that the parameterization of the model for the situation under study was satisfactory. When using the model for other situations, assumptions about the constant character and magnitude of most of the parameters should be checked through further research.

Differences between measured and simulated month to month NH_3 emissions (Table 3.2) appear to be more or less random. An explanation for the inconsistent character of these differences could be an incorrect assumption about the constant character of - in reality - time dependent parameters, such as urea concentration in the urine and urination frequency. A possible error in simulated emissions could also result from the assumption that the temperature of the emitting surfaces is equal to air temperature. Relatively warm urine and feces are deposited regularly on both the floor and the top layer of the slurry pit, leading to a temporary and local increase in temperature. Furthermore, evaporation of water takes place from the surfaces, resulting in a lowering of surface temperature. The net effect of these heat transfer processes is difficult to estimate, but is to be expected that the temperatures of the emitting surfaces will be somewhat lower than air temperature.

Although the assumption that air velocities are linearly dependent on air temperature (Equation 3.12) may be valid for the cow house under study because the ventilation system was designed to let the ventilation rate be linearly dependent on inside air temperature in the range from 8 to 18 °C (Kroodsma *et al.*, 1993), the assumption could not be tested because of lack of air velocity data. For naturally ventilated houses, ventilation rates will fluctuate greatly with time. More research is needed to relate local air velocities to the governing parameters (e.g. building characteristics, climatic conditions, ventilation system, temperature differences inside the house).

The sensitivity analyses showed that, except for urease activity, all parameters have a marked effect on simulated NH_3 emission. This effect is the most pronounced for pH. Various authors mention difficulties in determining and modeling pH of the puddle upon the floor and the slurry pit (top layer) in the framework of research into gaseous emissions from livestock buildings (Muck and Steenhuis, 1981, Anderson *et al.*, 1987). Both carbon dioxide and NH_3 are produced upon urea conversion. The faster volatilization of the former leads to a higher pH in the remaining liquid than the bulk pH, which, for Dutch cattle slurry, ranges from 7 to 8.5 (Hoeksma, 1988). Anderson *et al.* (1987) measured pH values as high as 9 in a mixture of ammonium hydroxide and carbonate, produced after urea conversion in an aqueous solution. Muck and Steenhuis (1981) determined an equation for pH depending on the concentration of urea in dairy cow urine. According to their equation, at the initial urea nitrogen concentration of 7.65 kg m^{-3} used in our study, the pH of the urine upon the floor should have been approximately 8. Because of the high sensitivity of the model for pH and the lack of research data, further research is necessary to improve insight into relationship of surface pH with, for instance, animal diet, slurry composition, processes in the slurry and local climatic conditions. In this framework, also the assumed value for K_a, where it is likely to depend on the measure of concentration of the liquid, and its relationship with temperature may need revision.

A sensitivity analysis on urea nitrogen concentration in the urine was not performed because the effect of $[U_0]$ (Equation 3.10a) is strictly linear (Smits *et al.*, 1995). Because changes in animal diet is expected to result in changes in the urea nitrogen concentration in the urine, the volume of urine produced and the urination frequency (Smits *et al.*, 1995), these parameters need combined attention when simulating the effect of diet on NH_3 emission. This could explain the inconsistency in differences between simulation and measurements for May and June when compared with the other months. The most pronounced effect of urea concentration is to be expected in May and June, when the animals were grazing outside during daytime. The consumption of fresh grass may have led to a change in the urea nitrogen concentration in the urine that altered measured NH_3 emission for both months when compared with simulations, in which a constant $[U_0]$ was used. A possible explanation for the fact that this effect is not supported by greater differences (Table 3.2) is that the effect of a change in urea nitrogen concentration may have been offset by a change in urination frequency.

From recent observations (Braam and Van den Hoorn, 1996; Elzing and Monteny, 1997), there are indications that the thickness of the urine puddle and the area per urine puddle slatted floors will be close to the values given in Table 3.1. The sensitivity of the results to these parameters A_{fl} and d_{fl} is therefore only relevant for cubicle houses with alternative floor designs (e.g. solid concrete, sloped solid concrete), where the value of these parameters will differ markedly from those for slatted floors.

The model has NH_3 production modules for the floor and the slurry pit. This means that the produced NH_3 upon the floor and in the slurry pit is assumed to emit from the cow house instantly, which will be true when averaged over a long term. To use the model for assessing slurry handling and management strategies, usually having impact on the short term NH_3 emission (e.g. the daily emission pattern), air exchange between the slurry pit and the inside air needs to be modeled. A possible explanation for the discrepancy in dynamics between measured and calculated emissions as shown in Figure 3.2 might be that NH_3 - although being produced - was only emitted from the slurry pit when conditions were in favor of air exchange, e.g. at night, when relatively cold outside air would enter the pit through the slats, whereas relatively warm incoming air (daytime) would not enter the pit and reduce its emission.

Time dependent parameters will have to be measured continuously to make short term emission modeling valid for the purpose indicated. In addition, the model assumption that the feces and urine are instantly and completely mixed to become the only source of NH_3 emission in the slurry pit needs attention. Completely mixed slurry in the pit will not be realistic on commercial dairy farms. In The Netherlands, for instance, mixing is only carried out just before emptying the slurry pit, which is done a few times per year. An alternative is to model urea conversion in the top layer of the stored slurry after urine deposition coming from the floor, in combination with diffusion of NH_3 in the slurry as described by Zhang *et al.* (1992). Also, modeling of the dynamic air exchange between the slurry pit and the air inside the building is needed for more realistic modeling of the slurry pit module.

Based upon findings by Elzing and Monteny (1997), urea can be regarded as the major source of NH_3 production for the floor module where conversions are rapid. However, the feces and urine will be stored in the slurry pit for a much longer period of time, depending on the storage capacity. Assuming that the capacity will generally be sufficient for a couple of months, organic nitrogen compounds will decompose during storage (Patni and Jui, 1991). The NH_3 produced following this decomposition may be significant when compared to the NH_3 production due to urea conversion. In future research, this source of NH_3 should be included in the slurry pit module and Equations 3.1b, 3.10b and 3.11 may need revision.

The model uses the NH_3 mass transfer coefficient given by Haslam *et al.* (1924) (Equation 3.7). This equation was determined for NH_3 desorption in a liquid film reactor. Based upon findings by Muck and Steenhuis (1981), Elzing *et al.* (1992) and Elzing and Monteny (1997), there are no reasons to doubt applicability of this equation for the film of urine upon a floor in a dairy cow house. However, Arogo *et al.* (1996) showed that empirically determined NH_3 mass transfer coefficients for stored manure could differ significantly from values obtained by using the equation from Haslam *et al.* (1924). A first analysis indicates that it would allow higher air velocities over the slurry pit surface compared to values used in our study. The validity of this change has to be tested by air velocity measurements in the slurry pit.

5 Conclusions

Simulation of NH_3 emissions from dairy cow housing on a monthly basis appears to be possible using a mechanistic emission model that includes the urination behavior of the cows. Results from a study in a commercially-operated, research dairy cow house with slatted floors and slurry storage inside the house had an absolute error of 3.8% relative to measured emissions from January to June. Maximal underestimation was 6% occurring in June and maximal overestimation was 7% for March. A comparison of daily measured and calculated NH_3 emission patterns, studied for a situation with and without part time grazing during daytime, indicated that dynamics of the model need improvement. A sensitivity analysis showed that pH has a marked effect on the NH_3 emission. Also, thickness of the urine film, area per urination, urea concentration in the urine and urination frequency had significant effects. The potential of the model to predict NH_3 emission levels for commercial dairy cow houses will depend mainly on the validity of assumed parameter values for those situations. Specific assumptions concerning the slurry pit module need further refinement to use the model for optimization of slurry handling and management strategies.

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4

pH of and gaseous emissions from urine after its excretion in a dairy cow house

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Abstract

Acidity (pH) is a dominant factor in the ammonia emission from dairy cow houses. In ammonia emission models for animal houses, a constant and equal pH value is assumed for urine that is excreted on slatted floors and in the pit. These assumptions are questionable because pH and volatilization of gases fluctuate with temperature and may also depend on the conditions on the surface upon which urine is excreted.

A laboratory experiment in a climate room was conducted to study pH development of dairy cow urine. Each of the 6 treatments consisted of urine application on either a concrete tile (specimen of a concrete floor) or the slurry surface at one of the three temperature levels (5, 10 or 15 °C), and was replicated. The pH of the layer of urine and the concentrations of ammonia and carbon dioxide in the air above the urine were continuously measured for 24 hours after urine application. An additional treatment (at 10 °C) was conducted in a dairy cow house.

Development of urine pH was mathematically described accurately by a combination of an exponential increase and a linear asymptote for all treatments. The exponential increase was completed the fastest for urine on tiles at 15 °C ($P<0.05$), whereas no difference was observed for exponential pH increase for the slurry treatments. The pH of the layer of urine on the tile increased approximately 1.0 pH unit during 10 hours after urine application, while the increase was significantly less (0.5 pH unit; $P<0.001$) for urine on slurry. Temperature had no significant effect on the pH increase.

The maximal level ammonia and carbon dioxide concentrations in the air above the urine increased with temperature. Furthermore, maximal ammonia concentrations for the tile treatments were greater (100-280 ppm) than for the slurry treatments (70-150 ppm), mainly due to a lesser pH level and a greater thickness of the layer of urine on slurry. Concentrations of carbon dioxide for the slurry treatments developed on greater levels, due to carbon dioxide mass transfer from the slurry.

The results of measurements in the dairy cow house were comparable with results from the laboratory experiment. This indicates that the assumptions about the pH in current ammonia emission models need revision. The equation and parameter values produced from data in this experiment will increase accuracy of model predictions.

Keywords: ammonia, ammonium, carbon dioxide, modelling, temperature, urease activity

1 Introduction

Slurry and urine acidity (pH) is a dominant factor in the ammonia (NH_3) emission following land spreading (Van der Molen *et al.*, 1990; Hutchings *et al.*, 1996; Sommer and Sherlock, 1996) and from houses for dairy cows (Elzing and Monteny, 1997a; Monteny *et al.*, 1998) and pigs (Anderson *et al.*, 1987; Aarnink, 1997; Ni, 1996). The production of NH_3 and carbon dioxide (CO_2) following enzymatic decomposition of urea in the urine excreted in animal houses is influenced by pH (See Figure 4.1), because urease activity is pH dependent (Muck, 1982). Furthermore, chemical equilibria in excreted urine excreted and in the slurry stored in pits [(NH_4^+)/NH_3 and CO_2/bicarbonate (HCO_3^-) /carbonate (CO_3^{2-})] and thus the amounts of the unionized fractions of the compounds (NH_3 and CO_2) available for volatilization are pH dependent (Sommer and Sherlock, 1996; Sommer and Husted, 1995a).

Models have been developed describing NH_3 production and volatilization inside animal houses, as a tool to predict NH_3 emission levels (Elzing and Monteny, 1997a; Monteny *et al.*, 1998), and to develop and assess emission reducing strategies, e.g. through slurry management (Muck and Steenhuis, 1981) or housing design and climatization (Aarnink, 1997; Ni, 1996). In these models, pH is either assumed to have a constant value based on results from limited measurements (Elzing and Monteny, 1997a) or derived from the fit of predicted and measured NH_3 emissions (Aarnink, 1997). This assumption, however, may well need revision. Sommer and Sherlock (1996) reported a quadratic increase in the slurry pH during the first hours of slurry storage, due to a greater initial volatilization of CO_2 (production of base; see Figure 4.1) compared to NH_3. This difference in volatilization rates is caused by the greater value of the equilibrium constants of CO_2 compared to NH_3 (Sommer and Husted, 1995b). On the other hand, the equilibrium constant of NH_3 increases more with temperature than CO_2 equilibrium constant, so pH will differ with temperature (Sommer and Sherlock, 1996). The pH of urine deposited on floors and of the top layer of a slurry pit are assumed to be equal in emission models (Aarnink, 1997; Elzing and Monteny, 1997a; Monteny *et al.*, 1998). This assumption can also be questioned. Little is known about the interaction between urine and the surfaces on which it is deposited, but it is expected that concrete floors and slurry surface have different impact on urine pH after its excretion.

Objective

The objective of the laboratory experiment described in this paper was to study the development of pH and concentrations of NH_3 and CO_2 after application of dairy cow urine on both fouled concrete floors and on stored dairy cow slurry. The experiment was conducted at 5, 10 and 15 °C to investigate the role of temperature.

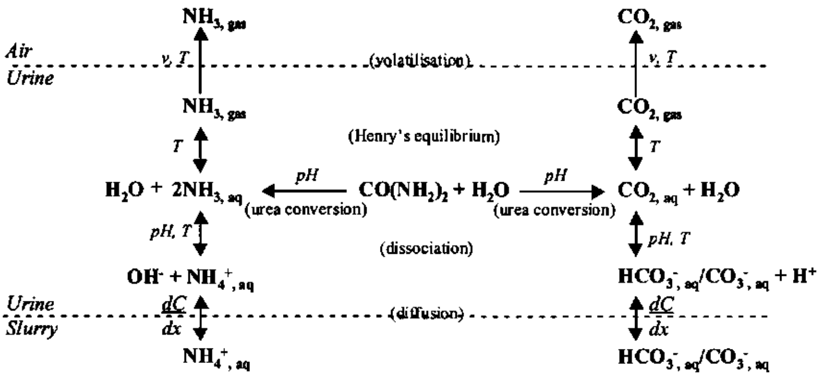

Figure 4.1: Schematic representation of nitrogen related processes in urine and slurry. pH = acidity; T = temperature; v = air velocity; dC/dx = concentration difference with height; aq = aqueous; gas = gaseous.

2 Materials and Methods

2.1 Equipment

The experiment was conducted in a climate room (Elzing and Monteny, 1997a) where temperature (T) and relative humidity (RH, kept constant at 80%) were controlled. Each treatment consisted of urine application on either a concrete tile or a slurry surface at one of the three temperature levels (5, 10 or 15 °C), and was replicated. The tiles were specimens of commonly used concrete floors, 300 x 300 mm x 70 mm (l x w x h) concrete pieces (comparable to patio blocks) having a composition and a surface roughness similar to floors in dairy cow barns (Braam and Swierstra, 1998). The slurry used was obtained from an operating dairy cow house. Figure 4.2 (A and B) shows the configuration of the equipment used during the experiment.

For the tile treatments, a 140 mm high bottomless plexi glas container (192 mm diameter, effective head space 2.2 L; Figure 4.2A) was placed on top of the tile. It had a rubber ring at the bottom edge to avoid leakage of urine. A similar but higher container (300 mm height, 6.8 L content; Figure 4.2B) with bottom was used or the slurry treatments. Both containers had a removable lid in which there was an opening for the pH sensor (Sentron 2001 pH). The sensor was calibrated (pH values of 7 and 10) at the start and at the finishing of each treatment. Sensor drift appeared to be no more than 0.1 pH unit, so measured pH values were not corrected. In addition to the pH sensor insert, the container lid had a port in the middle with an air sampling tube attached. The air sampling tube was insulated and heated to avoid condensation. Air was drawn through the system with a pump at a constant flow rate. Replacement air entered the containers through 20 holes (0.1 cm diameter) near the edge of the lid. The air flow rate was checked with an air flow meter at the beginning and the end of each treatment, and was constant at a value of 0.93 L min^{-1}. From this air flow, 250 mL min^{-1} was diverted to a NDIR multigas monitor (Brüel and Kjaer, type 1302) to determine concentrations of NH_3 and CO_2, and is described in detail by Van Ouwerkerk (1993).

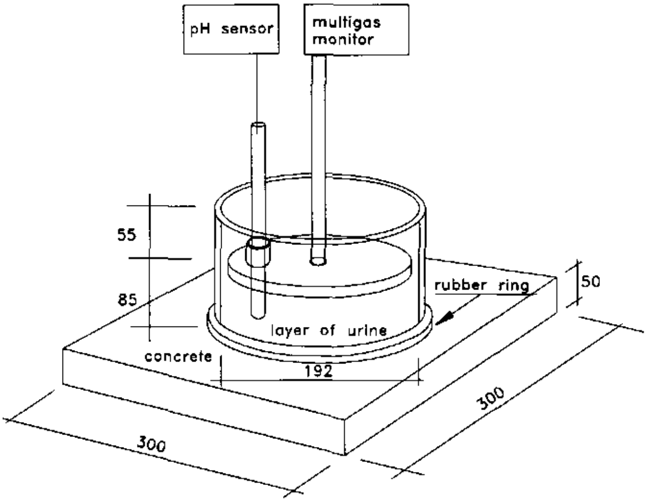

Figure 4.2A: Equipment configuration for the tile treatments (measures in mm).

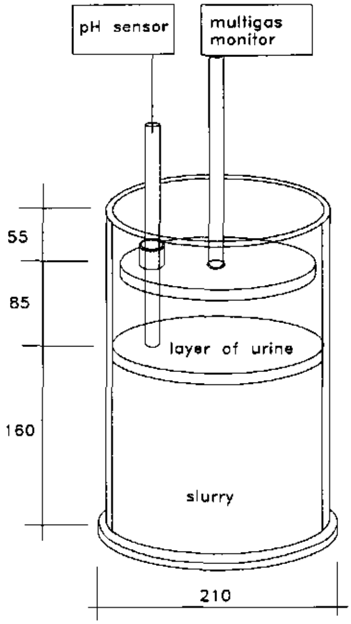

Figure 4.2B: Equipment configuration for the slurry treatments (measures in mm).

Climatic conditions, pH and gas concentrations were continuously recorded with a data logger and stored on a memory card. Measurements and data storage were controlled with a PC.

2.2 Slurry and urine

For all tile treatments, urine was collected from a group of 16 lactating cows housed in a cubicle house by sampling of successive urinations using a steel 1 L pan attached to a 3 m long stick. The cows were fed a diet of grass (65%) and corn (35%) silage, with additional concentrates. The urine was put into flasks of 100 mL. Urine from three flasks was analyzed for pH, mineral nitrogen (N_{min}, which is the sum of total ammoniacal nitrogen (TAN) and urea nitrogen (UN)) and total nitrogen (TN). All other flasks were immediately placed in a freezer and stored at –18 °C. The average results of the chemical analysis are given in Table 4.1. The average concentration of TN was 5.18 g kg^{-1}. For all slurry treatments, slurry and urine were collected on another day in the same dairy cow house (same diet composition). Slurry was immediately put into a jar and stored at 4 °C. Urine was treated and analyzed as described previously, except no TN concentrations were determined. The average analysis results are presented in Table 4.1. The differences in compositions shown in this table were most likely a result of a different nutrient content in the grass and corn silage, although the same relative amounts of these components were fed.

Table 4.1: Average N_{min} concentrations and range (g N L^{-1}) and pH (-) of three urine samples.

	Tile treatments	Slurry treatments
N_{min}	3.71 (3.69 – 2.72)	4.34 (4.19 – 4.59)
pH	8.2 (8.2 – 8.2)	8.5 (8.4 – 8.5)

Before the start of each slurry treatment, the jar with slurry was taken from the storage and its contents were homogenized. Then a 4.4 L portion was put into a container, sampled and analyzed for dry matter (DM), pH, TN and TAN. The results are shown in Table 4.2.

Table 4.2: Composition (g kg^{-1}) and pH (-) of the slurry used for the slurry treatments (see Table 4.3 for treatment codes).

	Treatment					
	S05-1	S05-2	S10-1	S10-2	S15-1	S15-2
DM	116	118	117	119	109	117
pH	7.4	7.2	7.3	7.1	7.9	7.4
TAN	1.52	1.49	1.46	1.44	1.60	1.60
TN	4.87	4.87	4.83	4.96	4.95	4.89

2.3 Treatments

Table 4.3 presents details of the treatments. Each treatment ran for 24 hours and was replicated.

Table 4.3. Overview of the treatments.

Treatment	Tile # or slurry	Room temperature (°C)	Volume of urine (mL)	Measurement time (h)
T05-1	1	5	35	24
T05-2	2	5	35	24
T10-1	1	10	35	24
T10-2	2	10	35	24
T15-1	1	15	30	24
T15-2	1	15	35	24
S05-1	Slurry	5	100	10
S05-2	Slurry	5	100	10
S10-1	Slurry	10	100	10
S10-2	Slurry	10	100	10
S15-1	Slurry	15	100	10
S15-2	Slurry	15	100	10

2.4 Volumes of urine

The volumes of urine used were based upon an average urine volume of 4 L per urination (Monteny and Erisman, 1998) covering 0.8 m^2 of slatted floor area and leaving a layer of 0.6 mm (Braam and Van den Hoorn, 1996). Thus, in the current experiment 17.4 mL upon the tile surface (290 cm^2) would represent practice. A volume of 35 mL of urine (30 mL for T15-1), resulting in a layer thickness 1.2 mm (1.0 mm for T15-1) was used instead to allow accurate pH measurements. Based on the assumption that the remainder of the urine excreted would flow to the slurry pit covering 0.8 m^2 of slurry, a volume of 100 mL (3.4 mm) used in the experiment represents practice.

2.5 Urease activity

Two concrete tiles were placed in the walking alley of an active dairy cow house for approximately 1 month to allow urease activity to develop. After cleaning of the tile surface using a scraper with a rubber strip, urease activity was determined *in situ* with the procedure described by Braam *et al.* (1997). In brief, urease activity was derived from the amount of TAN (expressed in mg of NH_3-N produced per L during 30 minutes) in a urea solution placed in a bottomless cylinder upon the tile surface.

2.6 Tile treatments

For each first replicate of the T05 and T10 treatments, one of the tiles used to determine urease activity was taken from the house. The tile was again placed in the house after the measurements were finished and the second tile was taken from the house for the second T05 and T10 treatment. The T15 treatment was repeated on the same tile (see Table 4.3). This tile was placed in the house again after the first replicate was finished. The time span between the replicates was one month.

The selected tile was allowed to adjust to the climatic conditions in the room for several hours, after the container had been put on top. During this period, gas concentrations were measured. A flask of urine was allowed to defrost in the climate room. After removal of the lid, urine was gently applied to the tile surface. The lid was replaced, the pH sensor was lowered until it touched the urine surface and pH measurement started and gas concentration measurements were resumed. To verify the results of the tile treatments, an additional treatment was carried out in the same dairy cow house where the urine and slurry had been collected. Freshly collected urine (35 mL) was applied on the slatted floor with a container placed on top. Only pH, ambient air temperature and NH_3 concentration were measured for a period of 4 hours following urine application, using the same measurement equipment as for the tile treatments.

2.7 Slurry treatments

The slurry filled container (Figure 4.2B) was put in the climate room. Measurements started after replacement of the lid and lowering of the pH sensor until it touched the surface of the slurry. After an over night adjustment to the ambient conditions (2 hours for S05-1), the lid and pH meter were removed and the surface was smoothened using a scraper with a rubber strip. The defrosted urine was gently applied to the slurry surface. After replacement of the lid, the pH sensor was lowered until it touched the urine layer surface and the measurements were resumed. When necessary, the level of the pH sensor was adjusted to the increased level of the slurry and urine, due to gas production in the slurry. Due to technical difficulties, gas concentrations were only measured for 8 hours during the S15-1 treatment.

2.8 Data selection and statistical analysis

Due to technical problems with the measurement equipment, treatment T10-2 had to be delayed with 1 day. As a consequence, the urine stayed defrosted in the climate room for 24 hours longer than the urine used in all other tile treatments. The measured data were not representative and therefore not taken into account. Measurements during T10-1 started at 2 hours after urine application due to technical problems. All other measurements for the tile treatments were successfully conducted for 24 hours after urine application. Due to gas production in the slurry, the level of the pH sensor had to be adjusted frequently to assure reliable data during the first 10 hours for the slurry treatments. However, no reliable pH values were measured during treatment S10-2 due to instability of the sensor. All gas concentration measurements were successfully conducted, except for S15-1 where concentration measurements had to be stopped after 8 hours due to power failure of the multi gas monitor.

Non linear regression analysis was carried out on the measured pH data using the following mathematical expression for the development of pH in time:

$$pH = A + B\,e^{-k\,t} + C\,t \qquad [4.1]$$

with:

pH = acidity (dimensionless)
A, B, C = constants
K = exponential coefficient
t = time (h)

This expression produces an exponentially increasing curve (e^{-kt}) with a linear asymptote (Ct). In the expression, (A+B) represents the pH at the moment of urine application (urine pH). The constant A is the asymptote of the exponential curve in case the linear part of Equation 4.1 (Ct) is ignored. Constant C represents the slope of the linear part of the equation, being d(pH)/dt, valid for $t > 0$.

An analysis of variance (ANOVA) with the statistical GENSTAT software (Anonymous, 1993) was conducted for the exponential pH increase and for the calculated (Equation 4.1) difference between pH at $t = 10$ hours and pH at $t = 0$, to test for effects of tile or slurry and temperature (block effect).

3 Results

3.1 Laboratory experiment

pH

In Figure 4.3 and 4.4, measured and fitted (Equation 4.1) pH development at various temperatures are presented for the tile and slurry treatments, respectively.

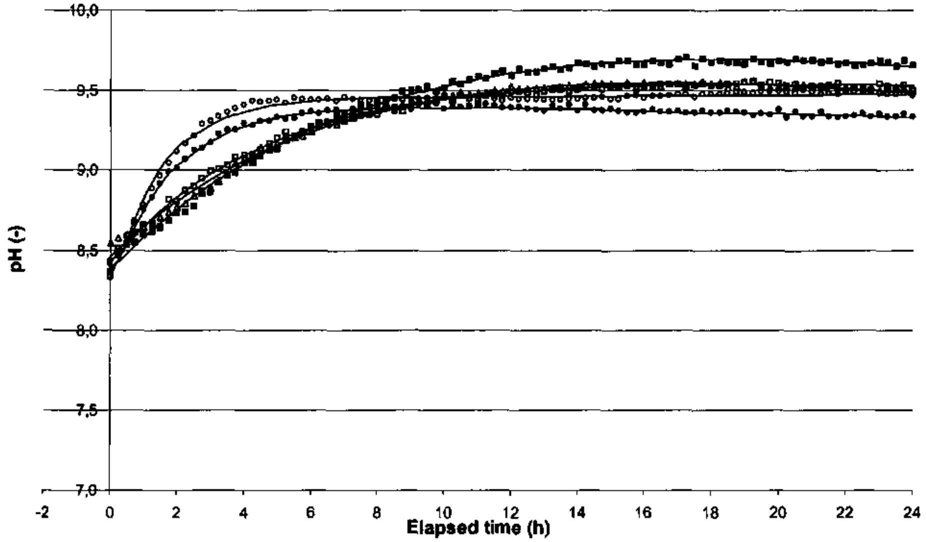

Figure 4.3: Measured (marker) and fitted (line) development of pH of urine applied on tiles at 5 °C (first □; second ■), 10 °C (first △), and 15 °C (first ○; second ●).

Urine pH increased exponentially during the first hours after urine application for all treatments and remained constant or developed slightly linear afterwards. The increase was from values between 8.4 and 8.5 (somewhat higher than the initial urine pH; Table 4.2) upon urine application to pH 9.4 to 9.6 reached after 24 hours for all tile treatments. The exponential increase was more rapid for the T15 treatments, whereas a slower and comparable exponential increase was observed for the T10 and T05 treatments. This is also shown in

Table 4.4, where the average value of e^{-k} is significantly less ($P<0.05$) for the T15 treatments compared to the T10 and T05 treatments.

The use of different tiles for the replicates of the T05 treatments (T05-1 on tile #1 and T05-2 on tile #2) apparently had hardly any effect on the development of urine pH. Only a slight difference in pH level was observed between the T15 replicates.

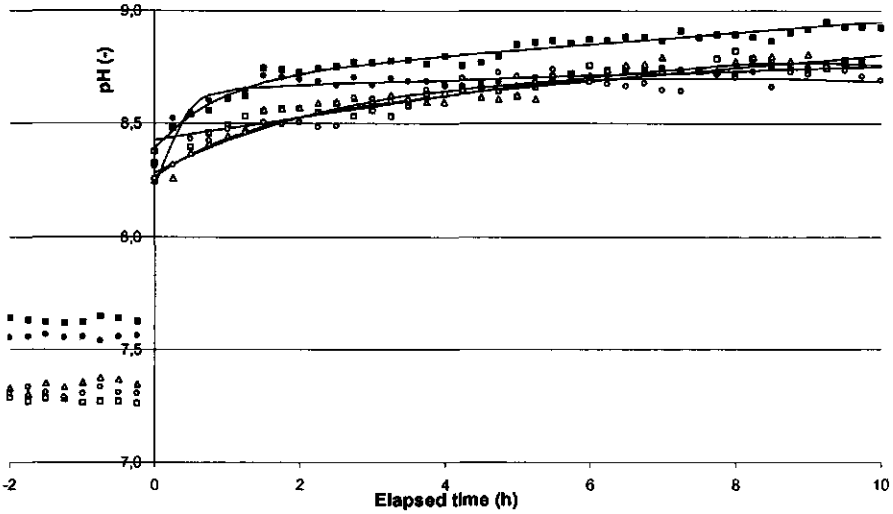

Figure 4.4: Measured (marker) and fitted (line) development of pH of urine applied on slurry at 5 °C (first □; second ■), 10 °C (first Δ), and 15 °C (first o; second •). Notice: different scales of x- and y-axes compared to Figure 4.3.

The pH of the urine applied on slurry increased from the pH of the slurry top layer (between 7.3 and 7.6) to the pH of the urine directly upon urine application (around 8.4). The combined exponential and linear pH development after urine application was to values between 8.7 and 8.9. Because of great variability of the replicates (Table 4.4), no significant effect of temperature on the exponential development was found. The pH of the urine in treatment S05-2 (10 hour period) and S15-2 (first 4 hours) developed to a greater level than observed in their replicates. This corresponded with the greater value of the pH of the slurry used for these treatments (pH around 7.6) when compared to their replicates (pH around 7.3).

The results of the non linear regression analysis are presented in Table 4.4. The percentages of accounted variance (R^2) were high, meaning that the regression model of a combined exponential and linear expression (Equation 4.1) fitted the measured data well. The lesser R^2 values and more variable e^{-k} values (including s.e.) for the slurry treatments when compared with the tile treatments were mainly caused by the need for adjustment of the level of the pH sensor to the increasing depth of slurry. The low s.e. values indicate high accuracy of all estimated parameter values. The only exception was S05-1. Sensor instability caused a highly fluctuating measured pH directly after urine application (not shown in Figure 4.3).

The negative values of parameter C for the urine applied on the tiles (except T15-1) indicate that urine pH showed a slight linear decrease after the exponential increase was completed. A slight linear increase was found for urine pH on slurry, except for S15-1.

Table 4.4: Estimated parameter values (s.e. between parenthesis) from non linear regression analysis of pH data for each treatment and means for all tile treatments and slurry treatments.

Treatment	R^2	e^{-k}	B	C	A
T05-1	99.6	0.818 (0.003)	- 1.23 (0.01)	- 0.005 (0.001)	9.66 (0.01)
T05-2	99.6	0.895 (0.003)	- 2.19 (0.06)	- 0.032 (0.002)	10.57 (0.06)
T10-1	99.4	0.873 (0.003)	- 1.64 (0.03)	- 0.023 (0.001)	10.10 (0.04)
T15-1	98.6	0.533 (0.005)	- 1.13 (0.02)	- 0.001 (0.000)	9.45 (0.00)
T15-2	99.3	0.619 (0.003)	- 1.10 (0.02)	- 0.005 (0.000)	9.45 (0.00)
Mean	86.7	0.769 (0.007)	- 1.13 (0.02)	- 0.002 (0.001)	9.56 (0.02)
S05-1	92.4	1.446 (0.215)	- 0.01 (0.01)	0.053 (0.006)	8.43 (0.01)
S05-2	97.0	0.328 (0.026)	- 0.31 (0.01)	0.025 (0.001)	8.70 (0.01)
S10-1	94.5	0.443 (0.050)	- 0.26 (0.02)	0.028 (0.001)	8.52 (0.02)
S15-1	90.1	0.747 (0.044)	- 0.65 (0.12)	- 0.021 (0.011)	8.93 (0.13)
S15-2	92.8	0.047 (0.008)	- 0.42 (0.01)	0.010 (0.001)	8.65 (0.00)
Mean	64.3	0.427 (0.054)	- 0.27 (0.02)	0.020 (0.002)	8.61 (0.02)

The increase in pH between t = 0 and 10 hours, calculated with Equation 4.1 using the parameter values in Table 4.4, appeared to be fairly constant and around 1.0 to 1.1 pH unit (average 1.03) for all tile treatments. For the slurry treatments this increase was between 0.33 and 0.56 pH unit (average 0.48). Temperature had no significant effect on the increase ($P>0.7$). The average increase for the slurry treatments was significantly ($P<0.001$) higher than for urine applied on slurry.

Ammonia concentration

Figures 4.5 and 4.6 show the development of NH_3 concentration in the container head space air, for the tiles and the slurry treatments, respectively.

Before urine application on the tiles, concentrations were between 5 and 40 ppm. This indicates the presence of TAN on the tile after its removal from the cow house. Ammonia concentrations decreased to low values at the moment of application of the urine (containing little TAN) followed by a strong increase directly afterwards. The level of NH_3 concentration after urine application increased with temperature. Ammonia concentration for T05-2 (tile #2) was greater than the concentration for the first replicate (tile #1). Moreover, maximal concentration was reached later in time. This coincided with greater urease activity of tile #2 (48.7 mg of NH_3-N produced per L of urea solution within 30 minutes versus 24.7 mg per L of urea for tile #1).

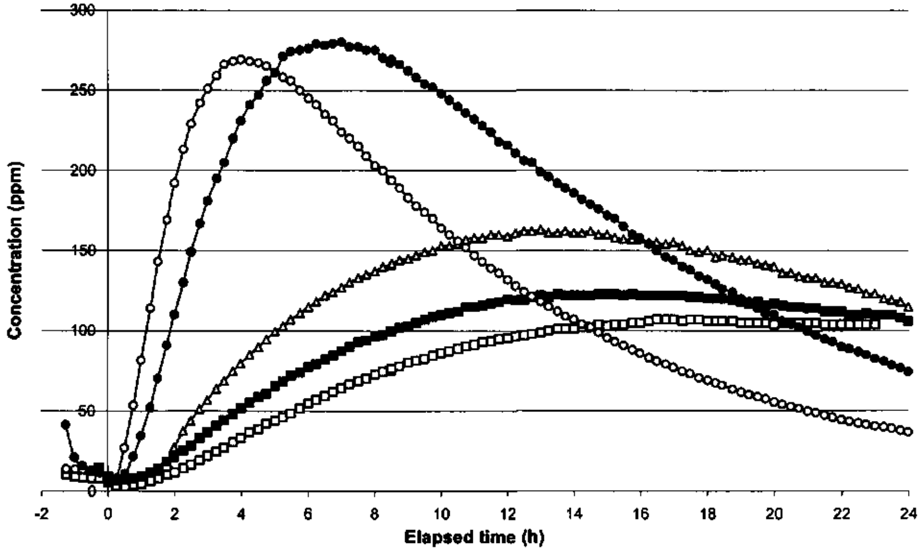

Figure 4.5: Development of NH_3 concentration for the tile treatments at at 5 °C (first □; second ■), 10 °C (first △), and 15 °C (first o; second •).

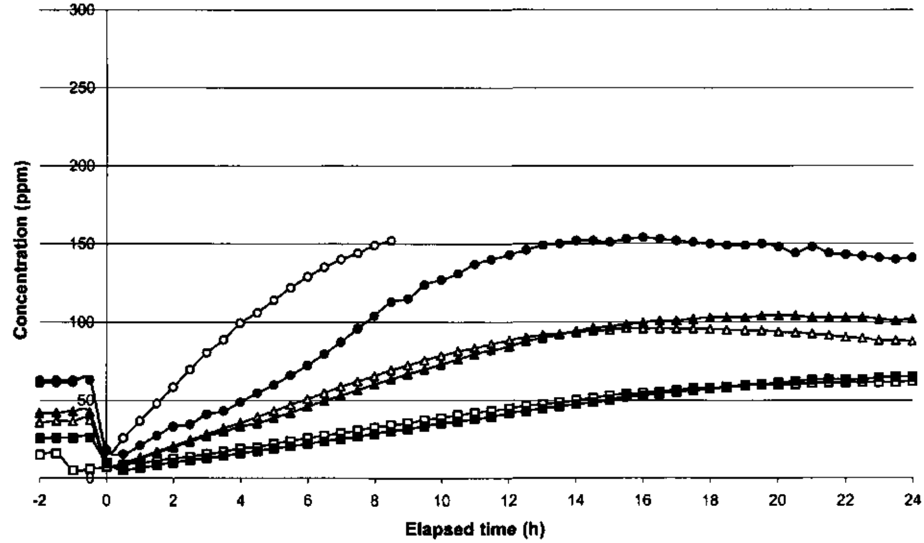

Figure 4.6: Development of NH_3 concentration for the slurry treatments at at 5 °C (first □; second ■), 10 °C (first △), and 15 °C (first o; second •).

Treatments T15-1 and T15-2 were conducted on the same tile (#2) but with different volumes of urine. Maximal NH_3 concentrations were comparable, because of no difference in urease activity. Ammonia concentration started to develop earlier and the maximal concentration was reached faster for T15-1. This was related to the thinner layer of urine (smaller volume, same surface area), enhancing transport processes of produced NH_3 in (diffusion) and from (volatilization) the film of urine on the tile, and thus the built up of NH_3 in the head space of the container.

After urine application on the slurry, NH_3 concentrations increased rapidly, with a high repeatability for the S05 and S10 replicates. The difference in development of the NH_3 concentration between the S15 treatments was high.

Except for similarity in the response to urine application and temperature, NH_3 concentrations developed to lesser levels for the slurry treatments than for the tile treatments despite higher concentrations before urine application. This was caused by the thicker layer of urine and the lesser pH levels. Concentrations decreased less within 24 hours, probably due to diffusive mass transfer of NH_3 from the slurry through the layer of urine.

Carbon dioxide concentrations

The development of CO_2 concentration for the tile and slurry treatments is presented in Figures 4.7 and 4.8, respectively. The level of CO_2 concentration development appeared to be positively related to temperature. For the tile treatments, CO_2 concentrations were high directly after urine application. This was unlike the strongly decreasing NH_3 concentrations (Figure 4.5). Except for T05-1, an apparent exponential decrease was observed to a level of between 500 and 550 ppm within 24 hours. These values represent the CO_2 concentrations of the ambient air, meaning that CO_2 production had stopped and all CO_2 was volatilized. The increase (between 6 and 19 hours) and decrease (between 19 and 24 hours) in CO_2 concentration for the T05-1 treatment could not be explained.

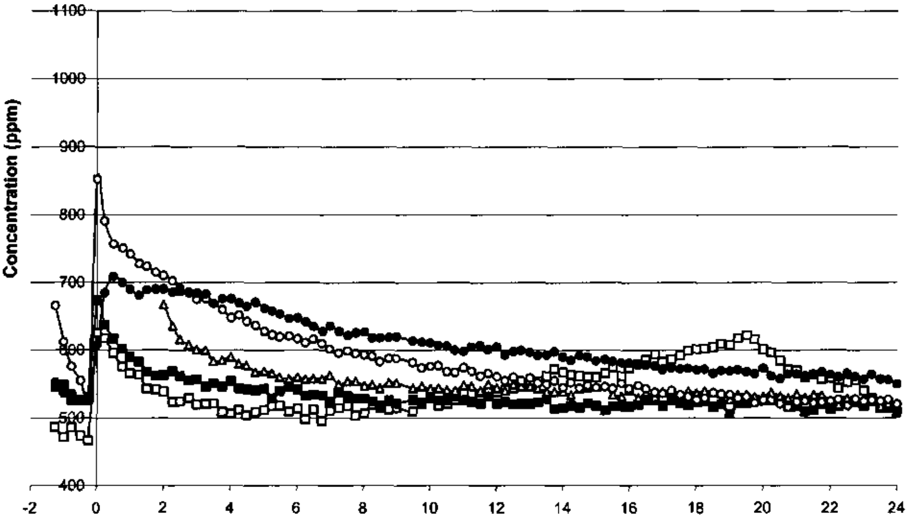

Figure 4.7: Development of CO_2 concentration for the tile treatments at at 5 °C (first □; second ■), 10 °C (first △), and 15 °C (first ○; second ●).

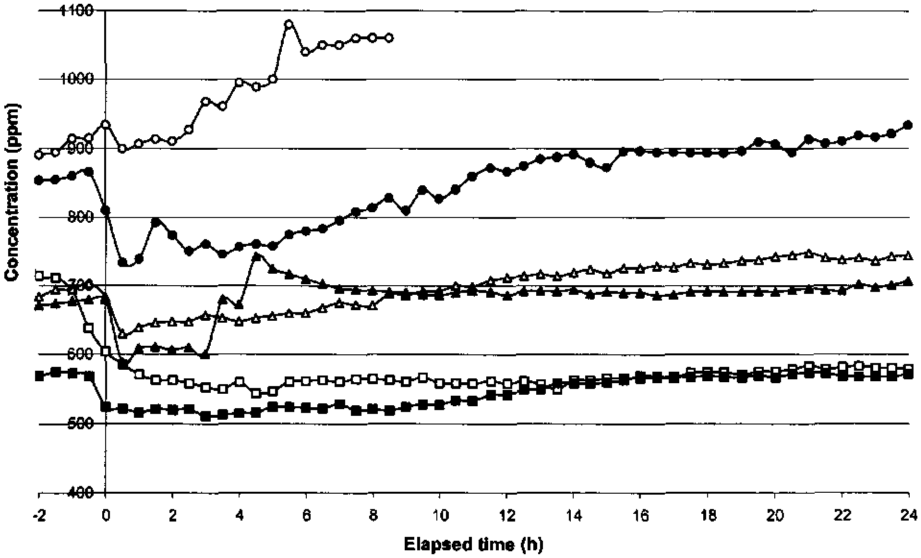

Figure 4.8: Development of CO_2 concentration for the slurry treatments at at 5 °C (first □; second ■), 10 °C (first △), and 15 °C (first ○; second ●).

Urine application on slurry (Figure 4.8) had a marked effect on the CO_2 concentration development. Similar to NH_3 concentrations, CO_2 generally concentrations decreased upon urine application. The steadily increasing CO_2 concentrations represent diffusive mass transfer of CO_2 from the slurry through the layer of urine. Repeatability of the development of CO_2 concentrations was high for the S05 and S10 replicates. Like for the NH_3 concentration, CO_2 concentration for S15-1 developed at a much greater level, which could not be explained.

3.2 Dairy cow house

Figure 4.9 presents the measured pH development of freshly collected dairy cow urine and the NH_3 concentration in the head space of the container placed on top of a concrete slatted floor and the data from treatment T10-1. Mean air temperature during the measurements in the dairy cow house was 10.7 °C.

During a period of 4 hours, the pH developed from 8.4 to 9.1 for the T10-1 treatment, whereas the increase was from 8.6 to 9.7 in the dairy cow house (3 hours). The increased level of pH development coincided with the greater level of development of NH_3 concentration, although differences in the patterns of pH and concentration development were substantial.

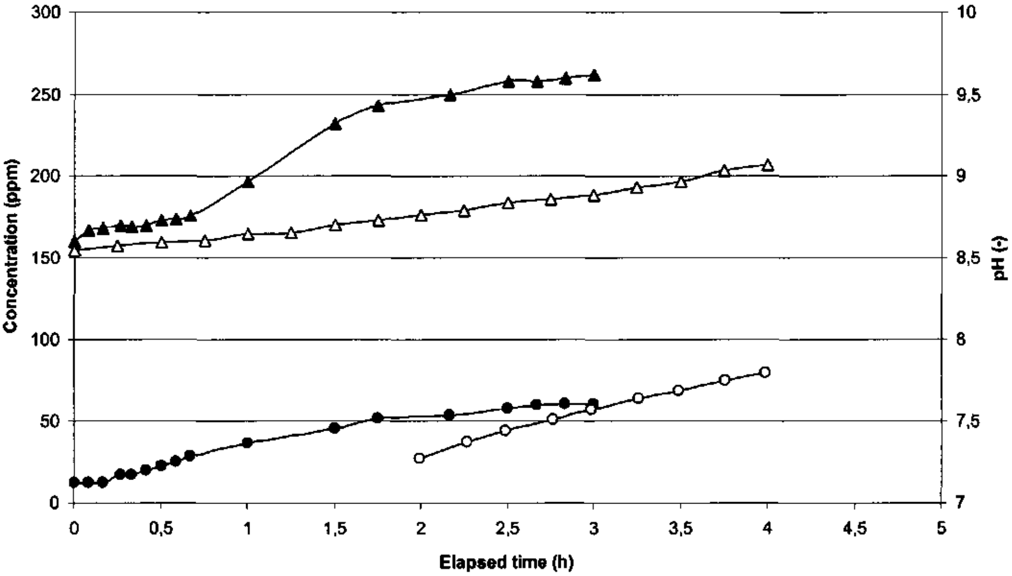

Figure 4.9: Development of pH and NH_3 concentration in the dairy cow house (pH: ▲; concentration: ●), and the T10-1 treatment (pH: △; concentration: ○).

4 Discussion

pH

The assumptions on constant and equal values of pH of urine on floors and in pits used in various models for NH_3 emission from animal houses (Muck and Steenhuis, 1981; Elzing and Monteny, 1997a; Monteny *et al.*, 1998; Aarnink, 1997; Ni, 1996) were not supported by the results of this experiment. An exponential increase and a linear development satisfactorily described the development of pH following urine application. This is in accordance with findings by Sommer and Sherlock (1996) about the pH development of stored cattle slurry. Moreover, the pH of urine was significantly higher for the tiles than for the urine on slurry. The indicative measurement in the dairy cow house (Figure 4.9) showed that even higher increases may be found in commercial dairy cow houses. Application of these findings in the emission models mentioned before would result in a higher predicted NH_3 emission from the floor, because greater amounts of volatile ammonia will be present in upon floors at higher pH values.

The lesser level of pH development for urine applied on slurry may well be explained by the dominant effect of slurry pH when compared to the effect of CO_2 and NH_3 volatilization.

The pH of urine on slurry increased by 1.3 pH unit when compared to slurry pH. An effect of slurry pH on the level of pH development after urine application was observed (Figure 4.4) but could not be statistically tested.

Gas concentrations

The relevance of the difference in development of the NH_3 (Figure 4.6) and CO_2 (Figure 4.8) concentrations for both S15 replicates has to be questioned because gas concentration measurements during treatment S15-1 had to be stopped after 8 hours due to a power failure and pH values were similar.

Comparison of the development of pH (Figures 4.3 and 4.4) with NH_3 and CO_2 concentration development for the tile treatments (Figures 4.5 and 4.7, respectively) shows that the time when maximal NH_3 concentration was reached roughly coincided with the time when exponential increase in pH had been completed. The concentrations of CO_2, however, seemed to develop autonomously. Because of a greater equilibrium constant of CO_2 compared to NH_3, most of the CO_2 produced following urea conversion will volatilize immediately, resulting in an increased pH (production of OH^-). The increased urea conversion and thus CO_2 production and volatilization at higher temperatures may, therefore, well explain the stronger exponential increase in pH at higher temperatures. At higher pH values, the NH_3/NH_4^+ equilibrium shifts to the left (Figure 4.1), and more NH_3 will volatilize. The consequent increased production of acid (H^+) will increasingly compensate the production of OH^- following CO_2 volatilization. This explains the change from an exponential increase to a linear decrease in pH development.

The increasing level of concentration development with temperature is related to the higher partial pressure of the gasses at the surface-air boundary, following Henry's law (Beutier and Renon, 1987) and the increasing volatilization (Elzing and Monteny, 1997b).

Ammonia concentrations and urease activity

According to Elzing and Monteny (1997b), the maximal NH_3 concentration is a measure of urease activity of the substrate where urine is deposited upon. At greater urease activities, more NH_3 is produced per unit of time from urea and consequently more NH_3 will volatilize, leading to higher NH_3 concentrations in the container head space (at the same air flow rates and pH). This was confirmed in the current experiment, where the higher urease activity of tile #2 resulted in higher maximal NH_3 concentration in treatments T05-2. Furthermore, the use of the same tile (tile #2) for the T15 treatments with the same urease activity was clearly demonstrated by the similar maximal NH_3 concentrations (Figure 4.5). The maximal NH_3 concentrations reached in the slurry treatments were markedly lower than in the tile treatments. This indicates a much lower urease activity for slurry, which is in accordance with findings of Elzing and Monteny (1997a), although also the lesser level of pH development and the thicker layer of urine will have contributed.

Relevance for dairy cow house and emission models

The results of the pH and NH_3 concentration measurements presented in Figure 4.9 give confidence that the tile treatments were representative for dairy cow houses. In spite of differences in location (cow house versus laboratory), time (e.g. differences in diet and urine composition) and exact conditions (freshly collected urine versus defrosted urine), development of pH and NH_3 concentration was comparable. Accuracy of the calculation of NH_3 emission using mechanistic models improves by including pH development according to Equation 4.1, using the mean parameter values from Table 4.4. To run these improved models, additional input data are needed about the pH of the top layer of the slurry, the floor pH (e.g. depending on the age of the concrete) and the pH of urine produced by the cows.

However, measurements of pH of urine on (slatted) floors and slurry in commercial dairy cow houses are hard to accomplish. Possibilities for mechanistic modeling of pH after urine excretion as a function of chemical equilibria (Sommer and Husted, 1995b) should, therefor, have to be investigated.

The measurements ran for 24 h and 10 h for the tile and slurry treatments, respectively. The relevance of these periods are indicated by Monteny and Erisman (1998), who estimated that the mean time between two successive urination on the same part of the slatted floor in fully occupied dairy cow houses would be around 10 hours. Furthermore, this time increases greatly in situations with a more extensive occupation or when outside grazing is conducted during day time.

5 Conclusions

1. Laboratory and in-situ treatments showed that urine pH increased at least 1 pH unit in 3 to 10 hours after urine deposition on floors. This increase was significantly greater than the 0.5 pH unit increase observed for urine on slurry. No significant effect of temperature was found on either of these increases.

2. The measured pH of urine applied on concrete tiles and on slurry was described satisfactorily by a combined exponential increase and a linear development with time. The exponential increase was completed faster at greater temperatures. After completion of the exponential increase, a slight linear decrease in pH was observed for urine applied on tiles, whereas a slight linear increase was observed in pH for urine applied on slurry. The exponential increase was mostly related to the characteristic development of CO_2 concentrations, whereas the linear development was explained by the NH_3 concentration characteristics.

3. Maximal concentrations of NH_3 were higher and were reached faster for urine applied on tiles than for urine on slurry. This was caused by the greater pH values of the urine and the lesser thickness of the layer of urine, although greater urease activity of the tiles compared to slurry may have contributed.

4. Mechanistic models which attempt to predict NH_3 volatilization from dairy cow houses should take into account the effects of site (separate modules for concrete or slatted floor and slurry pit) and time on pH values of the urine deposited on an emitting surface.

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5

Air exchange through a slatted floor for dairy-cow housing

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Submitted for publication

Abstract

Slatted floors are a common feature of cubicle houses for dairy cows. Air will flow through the slots, transporting gases like ammonia from the pits to the house. Laboratory and full scale experiments were conducted to study air flow characteristics of, and to quantify air exchange rates through slatted floors. In the laboratory experiment a ventilation box was used and forced ventilation and thermal buoyancy induced air flow through slots were separately studied. Air exchange rates were determined with the mass balance of carbon dioxide that was used as a tracer gas and injected in the box. For forced ventilation, pressure difference across the slots was linearly proportional to the kinetic energy, thus air flow was turbulent. This proportionality, representing the friction factor of the slots, was 1.60 for slats upright and 2.84 for slats reversed and was explained by the geometry of the slots. No such difference was found when air flow was induced by temperature gradients, because rise of warm air and fall of cold air took place simultaneously. Under those conditions, air flow resistance became independent of the geometry of openings. Air exchange rates through the slots were linearly related to the temperature difference across the slots in the range of 0-18 °C studied.

The *in-situ* experiment was conducted in a mechanically ventilated dairy cow house with 32 lactating cows. The air exchange rate was calculated from the mass balance of the tracer gas carbon monoxide injected in the pits. The ventilation of the cow house was set at 50% (13,000 m^3 h^{-1}), 75% (18,000 m^3 h^{-1}) and 100% (22,000 m^3 h^{-1}) of the maximum ventilation capacity. Four measurement periods of 6-8 days each and distributed over the year were chosen to obtain a large range in temperature differences between air in the pit and air that entered the house. At negative values of the temperature difference between air in the pit and outside air, the air exchange was constant at values of around 1,660 m^3 h^{-1}. From temperature differences of around 0 °C and greater, air exchange increased linearly proportional to the temperature difference. This was in accordance with the results from the laboratory experiment. The proportionality factor at ventilation rates of 75% and 100% was significantly greater than for 50%.

Keywords: air velocity, slots, tracer gas, buoyancy, forced ventilation, geometry, air exchange rate

1 Introduction

Slatted floors in walking alleys are a common feature of cubicle houses for dairy cows in Europe. Faeces and urine are transported through the slots of the floor by gravity and the animals' locomotion, to a pit beneath the slats. Bruce (1975) described the major drawback of slatted floors, namely convective air flow through the slats transporting hazardous gases (e.g. ammonia (NH_3), hydrogen sulfide) from the pit to the air inside the house, thus contributing to gaseous emissions from the house.

Few studies have been carried out on air flow and the consequent gaseous emissions from pits through slatted floors. Schulte *et al.* (1968) and Bruce (1975) qualitatively visualised the air flow through the slots using smoke. Bruce concluded that the air flow rate depended on the temperature difference between air below and above the floor (thermal buoyancy), on the ventilation system and the ventilation rate of the house (forced convection). Also the presence of animals upon the floor and the type and the weight of the animals in the house could be of influence. Yu *et al.* (1991) studied the air exchange rate through slatted floors at isothermal conditions (no buoyancy) in a scale model system, using the rate of decay of the tracer gas nitrous oxide (N_2O) released beneath the slats. Their results showed major effect on the air flow rate through the slots of the air speed and direction at the inlet, and due to ventilation rate and the direction of the air flow at floor level.

Because of difficulties in quantifying air exchange rates through slatted floors, the emission of ammonia from underfloor pits and from the floor surface has not been separately determined in emission surveys. Models such as the one presented by Monteny *et al.* (1998), although predict the rate of NH_3 being released from the pit and from the floor separately, simply add up both emission rates to obtain the total emission from the house. In active dairy cow houses, however, the NH_3 emission actually escaping from the pit depends on the air exchange rate through the slots. Monteny *et al.* (1998) suggested that pit emission is a dynamic process and that NH_3 concentrations in air beneath the slats may vary within relative short periods of time (e.g. because of accumulation) due to varying air exchange rates through the slatted floor.

In this study, air flow characteristics of slatted floors were studied and air exchange rates were quantified and modelled to enable quantification of NH_3 emission from the pit separate from floor emission. This paper describes laboratory and full scale experiments performed to study air flow characteristics of slatted floors and to quantify and model air exchange rates through the slots of a slatted floor.

2 Theory

The movement of air through a flow resistance (e.g. a slatted floor) is driven by a pressure difference over that resistance. The velocity of the airflow can be calculated when the pressure difference and the flow resistance are known. The pressure difference can be the result of forced convection, thermal buoyancy or both. These aspects are discussed separately to identify the governing equations for air exchange through slots of a slatted floor.

2.1 Forced convection

When air flow through a slatted floor is induced by forced convection, the pressure difference of the air at each side of the slots is generated by an existing local flow field. In cow houses, air is removed from the house by ventilation (mechanical or natural ventilation), inducing local flow fields at each side of the slot, thereby generating a local pressure difference. The shape and size of the floor opening (see Figure 5.1) and the flow regime determine the relationship between the pressure difference and the flow velocity (De Jong, 1990; Miguel, 1998). The flow regime is characterised by the Reynolds (Re) number. At low Re-numbers, the flow is laminar with prevailing viscous effects and the pressure difference is found to be proportional to the fluid velocity for Newtonian fluids like air, according to Darcy's law. For high Re-numbers, flow is turbulent and inertia effects prevail. Pressure difference is found to be proportional to the volumetric kinetic energy in the opening, and thus to the air velocity squared (Bot, 1983; De Jong, 1990).

For the flow regime developing from laminar (b = 0; Equation 5.1) to fully turbulent (a = 0; Equation 5.1), the relationship changes from linear to quadratic velocity dependency. This is accounted for in Forchheimers equation (Miguel, 1998).

$$\Delta P = a\,v + b\,v^2 \qquad [5.1]$$

For slatted floors, the type of relationship between pressure difference and air velocity has to be determined experimentally for the flow regime that is relevant for full scale dairy cow houses, because quantitative data had not been available.

2.2 Thermal buoyancy

If temperature decreases with increasing height, the warm air at low levels will have a relatively low density, and will rise, while the cold air at high levels will sink in the steady state. The vertical mass flux of rising warm air through a horizontal plane, e.g. through the slots of a slatted floor, will be equal to the mass flux of sinking cold air. Only if there is energy to generate such a negative temperature gradient (e.g. heating of air below or cooling of air above the floor), the air transport process continues and the warm and cold air are continuously mixed. On the other hand, if the temperature increases with increasing height, the low-density warm air will rest on the high-density cold air and no energy gradient will exist, thus making air stagnant.

In a situation with a layer of cold air separated from warm air (Figure 5.2), an arbitrary volume V_w of warm air will rise due to a net upward force F_{up} according to Archimedes principle:

$$F_{up} = g\,V_w\,(\rho_c - \rho_w) \qquad [5.2]$$

In this equation, density and temperature are assumed to be homogeneously distributed in respective layers.

The density difference $(\rho_c - \rho_w)$ is related to the temperature difference $(T_c - T_w)$ according to the ideal gas behaviour of air, thus:

$$F_{up} = -\,g\,\rho\,\beta\,V_w\,(T_c - T_w) = g\,\rho\,\beta\,V_w\,(T_w - T_c) \qquad [5.3]$$

The air volume can be defined by a reference height h_w and surface area A_w, so the local driving pressure difference ($\Delta P = F_{up} / A_w$) for the warm bubble of air will be:

$$\Delta P = g \rho \beta h_w (T_w - T_c) \qquad [5.4]$$

For a cold "bubble" of air with volume V_c containing the same mass as V_w, a similar approach results in the same pressure difference with β having the value of $1/T_c$ at T_c.

The general conclusion is that the driving pressure difference on the arbitrary warm and cold air bubbles (so called eddies) is proportional to the temperature difference. Moreover, combining Equations 5.1 and 5.4 shows that air velocity and temperature difference are linearly related at laminar air flow and that air velocity is related to the square root of temperature difference for turbulent conditions. Furthermore, a transition relation involving air velocity and temperature difference is found for air flow regimes in between laminar and turbulent conditions.

2.3 Air exchange rate

The air exchange rate due to forced air movement or thermal buoyancy can be calculated when the mean air velocity through the slots and the area of the slots are known:

$$\Phi = \bar{v} A \qquad [5.5]$$

For buoyancy driven, laminar air flow (low Re-numbers) a combination of Equations 5.1, 5.4 and 5.5 shows that the flow velocity and thus the air exchange rate is linearly proportional to the temperature difference. At high Re-numbers (turbulence) a linear proportionality can be expected to the square root of the temperature difference. A transition between linear and squared proportionality can be expected for air flow regimes between laminar and turbulent.

For vertical openings in greenhouses the square root dependency was found (De Jong, 1990). The same holds for situations with free air flow in animal houses (Randall, 1975; Bruce, 1977). The following experiments were initiated to extend the theory described in Equations 5.1 through 5.5 and to quantify air flow through slots in slatted floors for dairy cow housing.

3 Experiments

3.1. Laboratory experiments

3.1.1 Materials and Method

A cubic ventilation box (2.50 m; Figure 5.2) was constructed to allow controlled conditions for measurements of forced convection and buoyancy induced air flow through a slatted floor. An air tight wooden separation plate was installed at 1.75 m above the bottom of the box, with an opening of 1.1*1.1 m in the middle. Half a slatted floor element (original floor element: Figure 5.1) was placed in this opening. Each of the six slots was 35 mm wide at the top, 68 mm wide at the bottom and 935 mm long, resulting in a total slot area of 0.196 m^2 at the top and 0.381 m^2 at the bottom. The floor element could be placed in normal ("upright") or upside-down ("reversed") position to study the effect of flow direction through the non-symmetric openings (slots) of the slatted floor.

The trial consisted of two experiments, one with forced convection and one with thermal buoyancy driven air flow through the slatted floor element.

Forced convection

A ventilator (type ASAE A/S IP54 CL.F) was mounted in a pipe connected to the box, below the separation plate (Figure 5.2). The pipe also contained an anemometer for measurement of the ventilation rate. Ventilation rates varied from 0.05-0.33 m^3 s^{-1} and were increased with steps of 1%. A horizontal screen was installed between the ventilation opening and the separation plate to prevent large eddies in the space below the floor element

Thermal buoyancy

For the thermal buoyancy experiment, the ventilation pipe was sealed and a heating system was installed below the horizontal screen. The heating system controlled the air temperature below the separation plate.

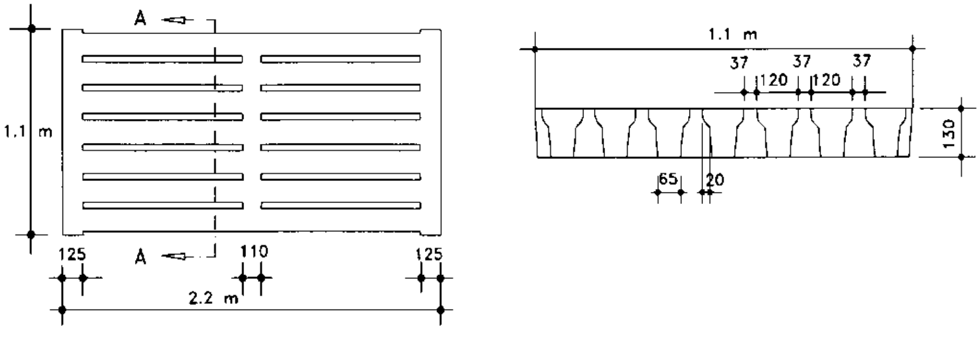


Figure 5.1: Top view and cross section (A—A) of the slatted floor element (except for length and width, all measures in mm).

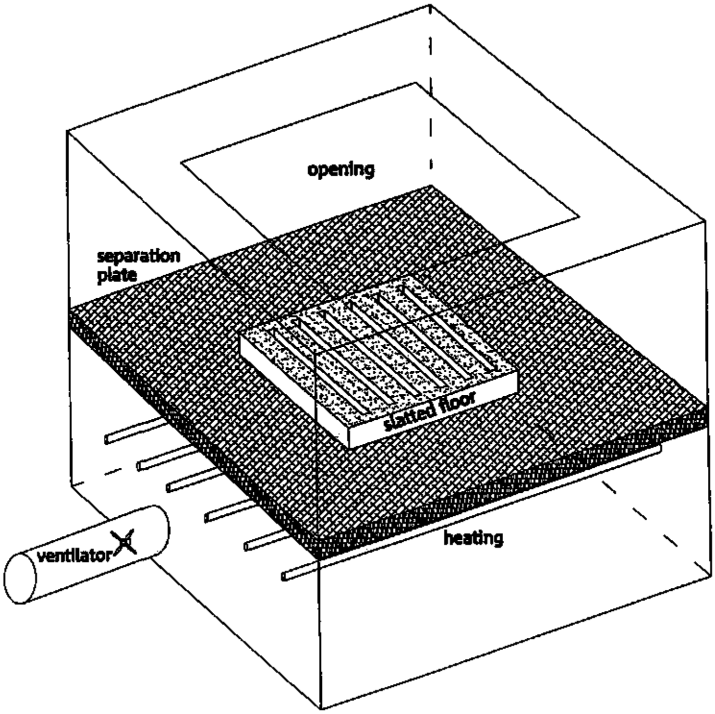


Figure 5.2: Schematic representation of the ventilation box with slatted floor element.

Carbon dioxide (CO_2) was used as a tracer gas to quantify the air exchange rate through the slatted floor element. It was distributed directly in the chamber below the separation plate through a circular injection tube system using a small ventilator (thermal buoyancy experiment). The amount of CO_2 injected was controlled by a mass flow controller. The CO_2 concentrations were measured at three locations below and at three locations above the separation, using individual sampling ducts attached to a multiplexer (manifold) and a CO_2 analyser (Fuji Infra Red Gas Analyser). Time lapse between sampling of two subsequent points was 1 min. Equation 5.6 was used to calculate the air exchange rate in the buoyancy experiments:

$$\Phi_M - \Phi_{V,\,slats}\,(C_{below} - C_{above}) = 0 \qquad [5.6]$$

The loss of CO_2 due to air sampling for gas analysis was neglected because of its small quantity compared to the injected amount of CO_2.

Static air pressure difference over the slatted floor element (one measurement point above and one below the floor element) was measured using a membrane pressure sensor (Validyne, model CD23). Air temperature was measured at six locations, three above and three below the slatted floor. Air was measured in four of the slots using hot wire sensors (Schmidt SS 20.01).

3.1.2. Results

Figure 5.3 shows the results of the experiments with forced air flow. Generally, the pressure difference appeared to be linearly proportional to kinetic energy (air velocity squared) of the flowing air. This indicates that the air flow regime was turbulent (a = 0, Equation 5.1). Air flow characteristics appeared to depend on the position of the slatted floor. The friction factor (b in Equation 5.1; slope in Figure 5.3) for air flow was 1.60 for the upright position and 2.84 for the reversed position. This difference is explained by the characteristic geometry of the slots in the slatted floor. The greater opening at the bottom of the slots (floor upright) caused less friction (upward air flow) than in the reversed situation, where air was forced to move through the smaller openings first and than expanded in the wider part of the slot (Figure 5.1).

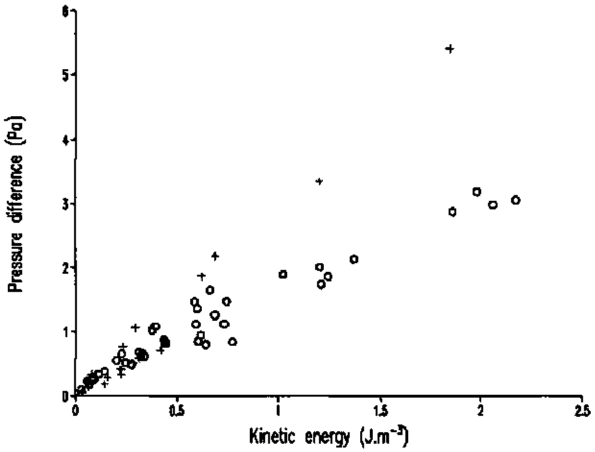


Figure 5.3: Kinetic energy versus pressure difference for the total range of air flow rates at ventilator induced (forced) air flow though a slatted floor element in upright (o) and reversed (+) position.

The measured air velocities in the slots ranged from 0.15 to 2 m s^{-1}, resulting in values for Re between 400 and 4,500.

The air exchange rate due to buoyancy alone is presented in Figure 5.4 for the two floor positions. Air exchange rate appeared to be unaffected by the positioning of the slatted floor. This can be understood from the fact that warm air was flowing upwards and consequently cold air was flowing downwards simultaneously. This is independent of the position of the floor. The approximately linear relation between air exchange rate, and thus air velocity, and temperature difference shows that the flow regime was in the laminar region. Air velocities were at or below 0.10 m s^{-1}, with Re-numbers of 250 and less. At a total slot area of 0.196 m^2, an air velocity of 0.10 m s^{-1} would result in an air exchange rate of 0.0196 m^3 s^{-1}, which is well in accordance with the maximum air exchange rate shown in Figure 5.4.

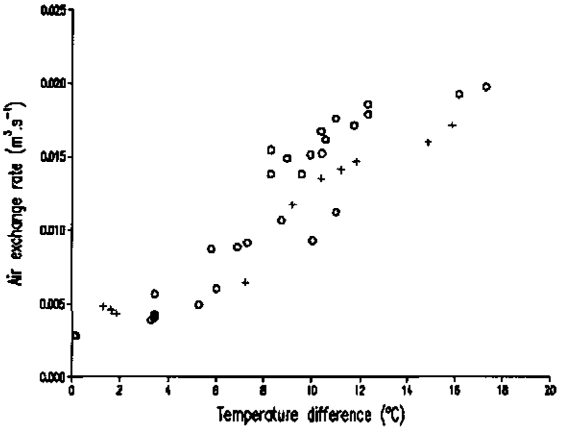


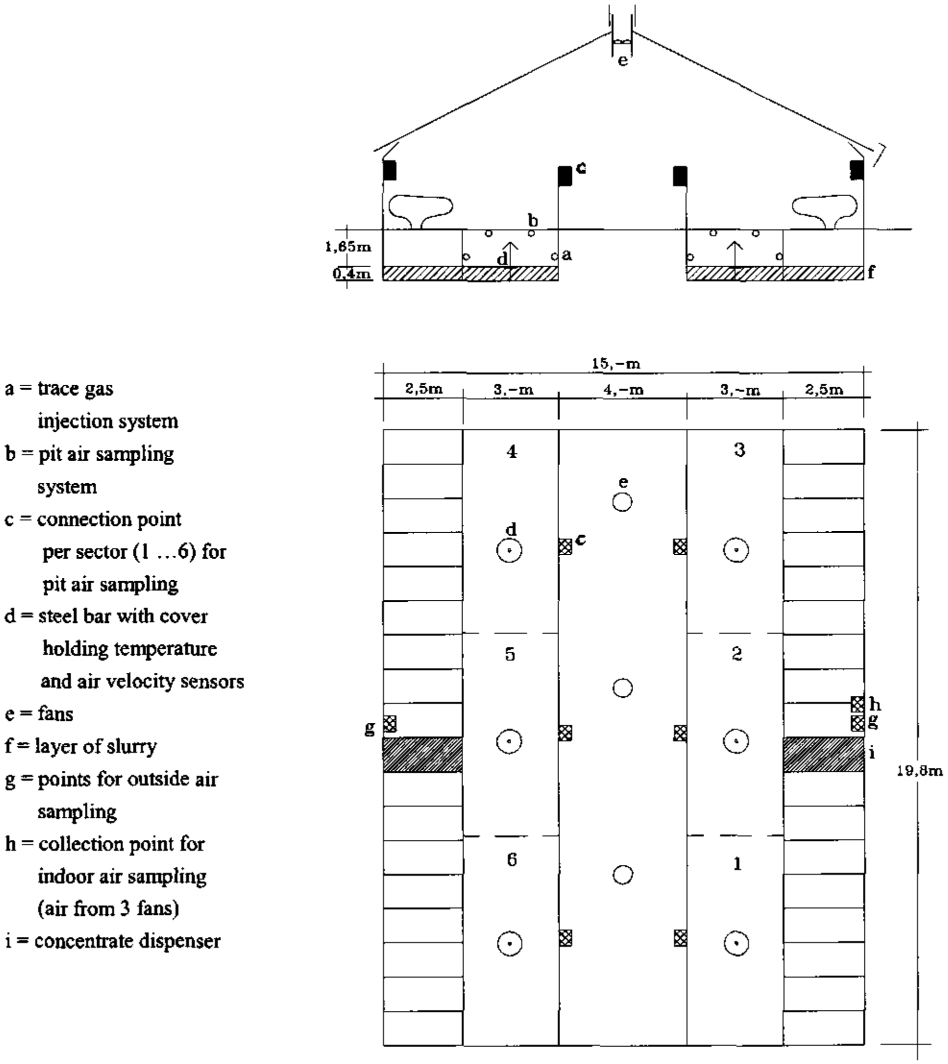
Figure 5.4: Thermal buoyancy induced air exchange rate through the slatted floor element in upright (o) and reversed (+) position as a function of the temperature difference at both sides of the floor element.

3.2 Full scale experiments

3.2.1 Material and method

Dairy cow house and ventilation

This work was conducted in a mechanically ventilated cubicle dairy cow house (19.8 m long and 15 m wide; volume: 1,350 m^3) at the experimental farm "De Vijf Roeden" in Duiven (Figure 5.5). The cow house had two rows of 17 cubicles each (2.5 m long and 1.2 m wide), two slatted floor alleys (slats 3 m wide) and a central feeding passage (4 m wide). The slatted floor alley was constructed of 36 floor elements (3.0 m * 1.1 m), each containing six slots (2.53 m * 0.037 m at the top). The total area (top) of the slots was 20.2 m^2. A 1.65 m deep slurry pit was situated under the alleys and the cubicles. The pits were not connected. Total slurry storage capacity was approximately 392 m^3. The slurry in the pit was at a level of approximately 0.4 m from the pit floor at the start of each experimental period. Three fans (Fancom type 1450T; maximum indicated capacity 8,000 m^3 h^{-1} each) were present in exhaust shafts, positioned at equal distances in the top of the roof. Air entered the building through a space boarded inlet system at the lateral sides of the building. Inlet openings were fixed at 0.02 m width during the experiments. The air exchange rate for the cow house was measured by continuous counting of pulses from fanwheel anemometers, placed in the exhaust shafts, directly under the fans. The relationship between the number of pulses from the anemometer and the air exchange rate were determined in a wind tunnel. The air exchange rate was normally related to indoor air temperature. However, during the experiment, air exchange rate was fixed at 50, 75 or 100% of maximal capacity. This corresponded with measured ventilation rates of 13,000, 18,000 and 22,000 m^3 h^{-1}, respectively.



a = trace gas injection system
b = pit air sampling system
c = connection point per sector (1 ...6) for pit air sampling
d = steel bar with cover holding temperature and air velocity sensors
e = fans
f = layer of slurry
g = points for outside air sampling
h = collection point for indoor air sampling (air from 3 fans)
i = concentrate dispenser

Figure 5.5: Plan and cross section of the mechanically ventilated cow house in Duiven, including the components of the measurement set up.

Cows and management

Thirty-two lactating, cross-bred Holstein-Friesian cows were present during the whole experimental period. The cows were milked twice daily, between 5:30 and 6:15 h and between 15:30 and 16:15 h in a separate milking parlour. As a consequence, no animals were present during those periods and the doors between the cow house and the corridor to the milking parlour were open. The diet consisted of grass and maize silage, administered once a day (usually around 8:00) using a mobile roughage mix-dosage unit. During the feed administration (15 minutes), the outside door was open. Additional concentrates were fed in an automatic concentrate feeding box; the amount of concentrates depended on the individual milk yield.

Tracer gas injection and sampling

Air exchange rate through the slots was determined using carbon monoxide (CO) as a tracer gas, injected under the slats. A duct containing polyethylene (PE) tubes for CO transport was attached to each of the four pit walls at 0.7 m above the pit bottom. Every 1.5 m, a tube end was stuck through a hole in the duct, creating an injection point. A total of 48 CO injection points were present, 12 on each pit wall. The number of injection points and their positions created an as equal as possible distribution of CO in the pit air. A mixture of compressed air (15 L min^{-1}) and CO, injected at a rate of 0.4 L min^{-1} directly after the compressor placed outside the house in a container, was equally distributed over the injection points using orifices (critical openings of 0.2 L min^{-1}) mounted in each tube near the injection point. Mass flows of compressed air and CO were continuously recorded.

Air in the pits was sampled through a system of teflon (FEP) tubes. The tubes were connected to 48 sampling points (12 sampling points per row and two rows per pit) attached to the bottom of the slats. Like the injection points, the sampling points were longitudinally equally distributed over the slatted floor area. The rows with sampling points were equally distributed over the width of the walking alley. Each pit was divided in three imaginary equal sectors, each containing eight sampling (and injection) points. Air sampling tubes per sector were connected in a box at the feeding fence near the sector to obtain a mix sample per sector. Equal tube lengths between the sampling point and the box assured equal volumes of air drawn from each sampling point. Air from the boxes was drawn through separate FEP tubes in a duct that was longitudinally connected to the feeding fence system. Air was also drawn from two outside locations (each one mounted at the side of the building just below the air inlet) and from each of the ventilation shafts. The air from the ventilation shafts was combined to a mix sample using 2 L min^{-1} orifices mounted at each sampling point. A central pump (4 L min^{-1}) took care of air transport from all nine sampling points to a CO analyser. Before being sampled, air passed a 12-channel multiplexer with 0.75 L min^{-1} orifices for each sampling point to assure continuous equal air transport per sampling point. Valves in the three remaining channels were permanently closed.

Concentration measurements

Each valve of the multiplexer was opened for 50 seconds allowing air being transported to an infrared CO analyser (Thermo Environmental Instruments Inc., model 48). A total measurement cycle took 8 minutes. By opening each valve of the multiplexer in sequence, air was sucked into the analysers using the analyser pump. The analyser was calibrated before and after each experimental period.

Other measurements and observations

In the middle of each pit section (see before), a steel bar was erected at equal distances to hold an AD592cN sensor for the pit air temperature (T_{pit}; at 0.8 m above the bottom of the pit, thus at approximately 0.4 m above the slurry surface). Temperature of the outside air (T_{out}) and the air inside the house (T_{house}) were continuously measured using sensors (type Rotronic Hygromer i100) placed near the air inlet of the cow house and at 2 m above floor level, respectively. Air exchange through the slatted floor and air velocity in the slots were studied visually on March 13 between 14:30 and 16:30 h. At that time, ventilation was 50% of the maximum ventilation rate. Airflow patterns were visualised using a minimist smoke machine.

Floor areas that acted as inlet and outlet were determined. Air velocities in four inlet slots and eight outlet slots were measured at that time with a Schmidt SS 20.01 hot wire anemometer.

Mass balance equations

Equation 5.6, applied for CO, was used to calculate the air exchange rate through the slatted floor. The maximum CO concentration for each pit (three sectors) was taken as value for C_{below}, because the sector with the greatest CO concentration acted as outlet. The CO concentration of the outside air was taken for C_{above}, because smoke tests showed that outside air directly entered the pit through the slots.

Experimental periods

Table 5.1 summarises the dates of the experimental periods and the ventilation rates for the cubicle dairy cow house.

Table 5.1: Overview of beginning and end of the experimental periods and sub periods and the ventilation rate of the cow house set.

Experimental period #	Ventilation rate of the cow house (% of maximal ventilation)	Number of days used for statistical analysis	Date and time of beginning and end
1			
- a	50	1	28 February 10:00 – 1 March 10:00
- b	75	2	1 March 10:00 – 3 March 10:00
- c	100	1	3 March 10:00 – 4 March 10:00
2			
- a	50	4	14 March 10:00 – 18 March 10:00
- b	75	4	18 March 10:00 – 22 March 10:00
3			
- a	50	3	10 May 14:00 – 13 May 20:00
- b	75	3	13 May 20:00 – 17 May12:00
4			
- a	75	3	13 October 13:00 – 17 October 09:00
- b	100	3	17 October 09:00 – 20 October 09:00

Originally, all ventilation rates were planned at a constant level for one day during each experimental period. To increase the system stability, longer measurement periods (3-4 days per ventilation rate set) were used in experimental period 2, 3 and 4.

Data acquisition and selection

Each 8 minutes, data were stored in the PC. The CO concentrations measured during the periods that doors were opened (e.g. during milking) were not analysed because of too much disturbance of airflow patterns. All data were averaged to hourly values.

Model and statistics

According to theory, the air exchange rate through the slatted floor would depend on the pressure difference over the slots caused by the ventilation system and the temperature difference across the slots (temperature of air in the pit and above the floor). Air exchange through the slots (Equation 5.6) was modelled as a function of the difference in temperature of the pit air and the outside air for each ventilation rate set and for all ventilation rates combined. The model used was a constant – node – linear model, based upon the results of the laboratory experiment described previously.

Data on air exchange rates and temperature differences for all days with the same ventilation rate were taken to fit the model, with the node occurring at 0 °C temperature difference. Values for the intercept (constant air exchange rate at negative temperature differences) and the slope (increase in air exchange rate per °C temperature difference) were calculated for each ventilation rate. Statistical analysis (ANOVA) was performed for each set of daily data, to account for dependencies in data on successive days. For each ventilation rate, a value for the slope was estimated for each day, taking one value for the intercept per ventilation rate. Mean and standard error of difference (s.e.d.) were calculated to judge significance of differences in the slope per ventilation rate.

3.2.2. Results

The calculated air exchange rates through the slatted floor are plotted against the temperature difference between the air inside the pit and outside air for 50% (Figure 5.6), 75% (Figure 5.7) and 100% (Figure 5.8) of the maximum ventilation rate. The numbers correspond with the measurement period (see Table 5.1).

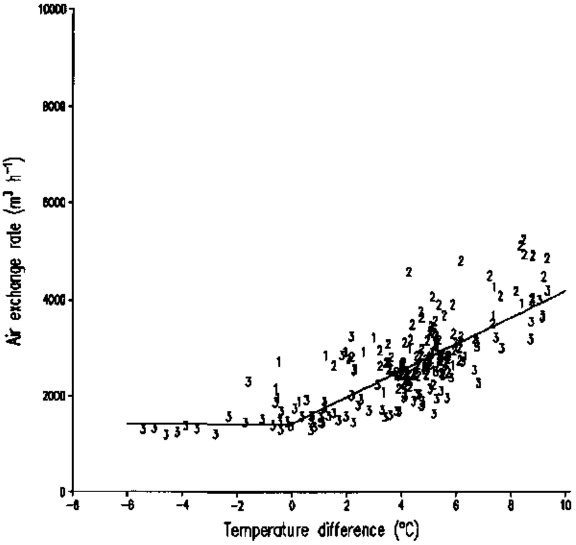


Figure 5.6: Air exchange rate through the slots versus difference in temperature of air in the pit and outside air at 50% ventilation rate of the dairy cow house. Numbers represent the measurement period. The line represents the constant - node - linear fit.

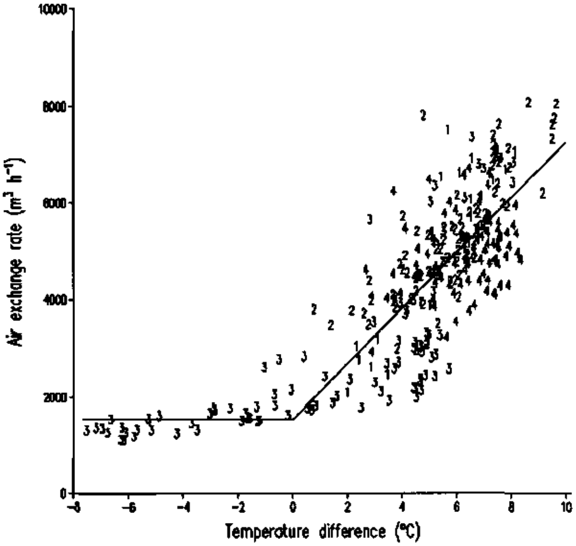


Figure 5.7: Air exchange rate through the slots versus difference in temperature of air in the pit and outside air at 75% ventilation rate of the dairy cow house. Numbers represent the measurement period. The line represents the constant - node - linear fit.

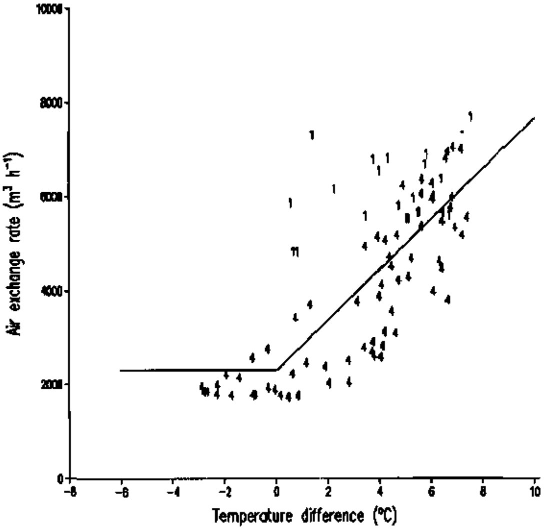


Figure 5.8: Air exchange rate through the slots versus difference in temperature of air in the pit and outside at 100% ventilation rate of the dairy cow house. Numbers represent the measurement period. The line represents the constant - linear - node fit.

At all ventilation rates, the air exchange rate was low and constant when negative temperature differences occurred. In these situations, the temperature gradient was towards the pit air and no buoyancy occurred (stagnant air in the pit). From temperature differences of around 0 °C upward, air exchange rates increased. Negative temperature differences mainly occurred in period 3 (May) and 4 (September). Moreover, the range of temperature differences observed was greatest in period 3. This is related to the great differences between day and night temperatures observed during spring in North-Western Europe. The temperature of the air inside the pit is influenced by the outside air entering through the slots but also by the relatively constant slurry temperature and will, therefore, fluctuate less.
The line plotted in each figure represents the fitted model. The results of the parameter estimation are shown in Table 5.2.

Table 5.2: Estimated parameter values for the constant - node - linear model of air exchange rate through slatted floors and temperature differences between pit air and outside air at various ventilation rates (VR in % of maximum). R^2 represents the percentage of variance accounted for by the model.

VR	R^2	Intercept ($m^3 h^{-1}$)	Slope ($m^3 h^{-1} °C^{-1}$)
50	60	1,426 ^{a}	274 ^{a}
75	68	1,547 ^{a}	572 ^{b}
100	53	2,299 ^{b}	536 ^{b}
All	43	1,656	447

Parameters with a different superscript differ ($P < 0.001$).

At negative temperature differences, air exchange rate through the slots was around 1,660 $m^3 h^{-1}$, based upon all data points. A value of 0 would be theoretically expected, because the relatively colder pit air would cause a stagnant layer of air and no (relatively warm) outside air would enter the pit. The findings from this experiment indicate that other parameters than the ones taken into account in the model will have played a role, like construction elements that disturbed air flow patterns and animal movement and dunging behaviour. Smoke tests indicated that construction elements of the roof were found to bend the air flow downward under all conditions. This observation, combined with the quadratic relationship between energy content of air and air velocity, then accounts for the increasing value of the intercept at increasing ventilation rates. Furthermore, smoke tests demonstrated local rise of air through the slots at locations where cows were standing (convective air movement; e.g. at the feeding boxes; sectors 2 and 5, Figure 5.5) and at places where warm urine and faeces were deposited. The increase in air exchange rate per unit of temperature at positive temperature differences, represented by the slope, was at 75 and 100 % of the maximum ventilation rate significantly greater than for 50%. The increase in energy content of the, mechanical ventilation induced, air flow at greater air exchange rates accounts for this. No significant difference was found for 75% and 100% of the maximum ventilation rates, indicating that thermal buoyancy effects prevailed.

The measurements of the air velocity in the slots resulted in mean air velocities of 0.14 (0.08-0.20) m s^{-1} in slots where air entered the pit (inlet) and in mean air velocities of 0.06 (0.01-0.11) m s^{-1} in slots were air was leaving the pit (outlet). This indicates that, at equal volumes of air entering and leaving the pit, the surface area of the outlet slots would be around twice as great as the surface area of the inlet slots. The slatted floor geometry (Figure 5.1) and the number of slatted floor elements yield a total slot area of 20 m^2. Based upon smoke tests, an area of 14 m^2 was estimated to act as outlet and 6 m^2 as inlet. Given the temperatures at the time of the measurements (T_{out} 9.5 °C; T_{pit} 13.2 °C), the air exchange rate would be around 2,300 m^3 h^{-1} (Figure 5.6), thus the air velocity in the outlet slots would be 0.05 m s^{-1}. This corresponds well with the measured values.

Smoke tests showed that parts of the slatted floor of sectors 2, 5 and 6 (see Figure 5.5) mostly acted as outlet and that the slatted floor of the other sectors were mainly inlet. This means that air in the pits moved not only vertically, but also horizontally.

4 Joint discussion

The results from the laboratory experiment with forced ventilation showed that turbulent air flow through the slots prevailed for the whole range of air exchange rates and air velocities in the range of 0.15 to 2 m s^{-1} and that the friction factor depended on the direction of the air flow relative to the slot geometry. Based upon measurements in the slots of slatted floors in a dairy cow house, however, air velocities were mostly in the bottom part of the indicated range. This can also be derived from the maximum air exchange rates determined in the cow house experiment (10,000 m^3 h^{-1}; see Figures 5.6 through 5.8), which corresponds with maximum air velocities of 0.20 m s^{-1} under the assumption that 14 m^2 of the total slot area would act as outlet. It is, therefore, most likely that air flow through slatted floors in dairy cow houses will be in the laminar region, with no effect of the direction of the air flow (Figure 5.2).

In the laboratory experiment, forced convection and thermal buoyancy induced air flow through a slatted floor were studied separately. In the mechanically ventilated cow house, however, both effects occurred simultaneously. But the linear relation between temperature difference and air exchange rate derived from the thermal buoyancy laboratory experiment was found to be very evident for the active cow house too. Thermal buoyancy (at temperature differences above 0 °C) prevailed in the cow house and an additional effect of the mechanical ventilation was only observed when ventilation rate was increased from 50% to 75% of the maximum (Figures 5.6 and 5.7).

In the data analysis for the cow house experiment, the temperature difference between the air in the slurry pit and the outside air was taken as explanatory variable for the air exchange rate through the slots. In theory, the temperature difference between the air in the pit and the air above the floor (indoor air at ideal mixing) should be taken as explanatory variable. The same holds for the difference in CO concentration used to calculate the air exchange rate (Equation 5.6). Taking outside air temperature and CO concentration as a basis for data analysis was based upon indicative smoke tests performed, showing a rapid fall of incoming air towards the slatted floor, especially at low outside air temperatures. Moreover, the location of the sensors for indoor air temperature (2 m above the floor) and indoor air sampling (at the ventilators placed in the roof) did not result in representative temperature and concentration data for the air above the floor, since ideal mixing is not to be expected in the cow house. At zero ventilation rate, only thermal buoyancy induced air flow through the slots will occur and the temperature difference between air inside the pit and air inside the house should be related to the air exchange rate. It is to be expected that the relevance of the temperature difference between air inside the pit and outside air will increase at increasing ventilation rates.

In the range of temperature differences studied in the laboratory experiment (0-18 °C), a linear relation between temperature difference and air exchange rate, and thus with air velocity, was found. This indicates that laminar air flow prevailed. The range of air velocity measured in the slots, 0-0.10 m s^{-1}, was comparable with the air velocities measured in slots of active cow houses and derived from air exchange rates calculated relative to the area of the outlet slots.

Figures 5.6 through 5.8 clearly show the influence on temperature difference (thermal buoyancy) and ventilation rate on the air exchange through the slatted floor. However, data points per ventilation rate (VR) percentage and per measurement period were scattered, resulting in the values for R^2 and standard errors reported in Table 5.2. The wind direction and wind speed may have played a role, although the air inlet system of the cow house was constructed to minimise wind influence and the air inlet was small (0.02 m wide). The contribution of the cow activity, however, could not be quantified.

The results can be used to quantify NH_3 emission (product of air exchange rate and NH_3 concentration) from the slurry pit in active dairy cow houses and to predict the emission reduction potential of measures applied in pits (e.g. alternative floor systems with greater air flow resistance, slurry cooling). Furthermore, the results may improve insight in the potential of climatisation of dairy-cow houses with the goal of reducing NH_3 emissions. Better mixing of incoming air and air inside the cow house might result in smaller temperature differences between incoming air and air inside the slurry pit, thus reducing air exchange between slurry pit and indoor air. Because of reduced air flow rate from the slurry pit, less NH_3 would be produced in the slurry pit (reduced air velocity at slurry level; built up of NH_3 beneath the slats reducing the mass transfer; Monteny *et al.*, 1998) and less NH_3 is transported from the slurry pit to the air inside the house.

5 Conclusions

1. The friction factor of slots in a slatted floor for dairy cows, determined under laboratory conditions for a convective turbulent air flow regime, depended on the direction of the air flow through the slots.

2. A linear, position independent, increase of the air exchange rate through the slots with the temperature difference over the slots was found in situations when air flow was induced by thermal buoyancy. Air flow appeared to be laminar.

3. A similar linear relation was also found in an experiment conducted in a mechanically ventilated dairy cow house, taking the difference in temperature between air inside the pit and outside air as explanatory variable.

4. The increase in air exchange rate with temperature difference depended on the ventilation rateof the cow house and was greater at low ventilation rates.

5. The model used to describe the relation of air exchange to temperature differences can be used to improve predictions of gaseous emissions from pits in cow houses with slatted floors and will allow quantification of emission reduction by floor and underfloor related emission reducing measures.

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Notation

A = area (m^2)
a = laminar air flow coefficient depending on geometry and fluid properties (with dimension)
b = turbulent air flow coefficient depending on geometry and fluid properties (with dimension)
C = concentration ($kg\ m^{-3}$)
F = force (N)
g = acceleration of gravity ($m^2\ s^{-1}$).
ΔP = pressure difference (Pa)
v = air velocity ($m\ s^{-1}$)
$\bar{v}$ = average air velocity ($m\ s^{-1}$)
T = temperature (K)
V = volume (m^3)
ρ = density ($kg\ m^{-3}$)
$\bar{\rho}$ = average density ($kg\ m^{-3}$)
β = expansion coefficient (K^{-1}), which has the value of $1/T_w$ at T_w.
Φ_V = air exchange rate ($m^3\ s^{-1}$)
Φ_M = mass flow rate ($kg\ s^{-1}$)

Subscripts:

below = below the slatted floor element
above = above the slatted floor element
slats = through slats
house = inside the cow house
out = outside
up = upward
w = warm
c = cold

6

Model prediction of ammonia emission from cubicle dairy cow houses: contribution of slatted floor and slurry pit

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Abstract

To facilitate separate quantification of ammonia emissions from the slurry pit and the floor in a cubicle dairy cow house, a mechanistic model for the production of ammonia was extended by adding ammonia mass balance equations for the slurry pit air and the air above the slatted floor. Furthermore, new information on the development of urine pH after its deposition on floors and in the pit was included. Model input data were collected in a mechanically ventilated cubicle house with 32 head of lactating dairy cows. The data were collected during three experimental periods of seven to eight days distributed over a year, ensuring a wide range of climatic conditions. The measured ammonia emission from the house and the measured ammonia concentration of the air inside the pits were compared with model predictions to evaluate the model performance.

The model performed well with adapted values of parameters in the air exchange rate equation for all experimental periods. Moreover, the pH of the top layer of the slurry pit had to be adapted to obtain a good fit for periods 2 and 3. This could be related to the difference in the composition of the slurry top layer. Ammonia emission from the slurry pits contributed on average for 25-40% to the instantaneous emission from the cow house. Maximum contribution was around 80% and occurred in situation with great differences in temperature between outside air and pit air, thus with great air exchange rates through the slatted floor. Fluctuations in ammonia emissions from the house greatly coincided with the fluctuations in pit emission. Measures that reduce the ammonia emission from the pit, therefore, should be developed taking the dynamics of the pit emission into account. The improved ammonia emission model can in this perspective be a powerful tool to assess fluctuations in the contribution of the pit and the floor to the emission from the house, and also to support the design of separate emission abatement strategies for pit and floor and for strategies.

Keywords: ammonia mitigation, pH, air exchange, slatted floors, model validation

1 Introduction

The emission of ammonia (NH_3) from dairy cow houses depends on factors related to dimensions and lay-out of the housing system, stocking density, diet with the consequent composition of the excreta, handling of the excreta and climatic conditions (Monteny and Erisman, 1998). Ammonia originates from urea as a major component of urine that cows excrete. In a traditional cubicle house for dairy cows, a part of the urine deposited on the slatted floor drains through the floor slots to the slurry pit beneath the floor. Depending on the duration of indoor storage, some NH_3 may be produced from decomposition of organic fecal nitrogen.

Because of the need to reduce NH_3 emissions for the sake of environmental protection, emission abatement strategies should focus on reduction of the emission from both the floor and the pit in dairy cow houses. However, the separate contribution of these two sources to the total emission from the house is hard to establish and complex measurement strategies are necessary to achieve this. This makes it difficult to assess the exact impact of indoor emission reduction measures and strategies. A mechanistic NH_3 emission model for cubicle houses for dairy cows was developed as an alternative for the assessment of NH_3 emission levels and mitigation options (Monteny *et al.*, 1998). That 1998 model consists of separate modules for NH_3 production from urine pools randomly distributed on the floor and from the pit. The NH_3 emission from the cow house was calculated as the sum of the floor and pit production. The authors discussed the need to improve the model to enable a separate quantification of the release rate (emission) of NH_3 from floor and pit, and to facilitate a realistic assessment of emission reducing measures for both emission sources. Moreover, NH_3 concentrations in the air above the urine pools on the floor and the slurry in the pit were neglected and constant values for the pH of the floor and the slurry were used in the 1998 model, thus possibly introducing a fundamental error in the model predictions. An improved emission model, based upon more realistic NH_3 mass balances for the pit air and the cow house, is presented and validated against measured NH_3 emission in this paper.

2 Materials and Methods

The modules for NH_3 production from the pit and the floor in the 1998 model were replaced by NH_3 mass balances for the volume of air in the slurry pit and the air volume above the floor (Figure 6.1). The module for the distribution of the urinations over the slatted floor area remained unchanged.

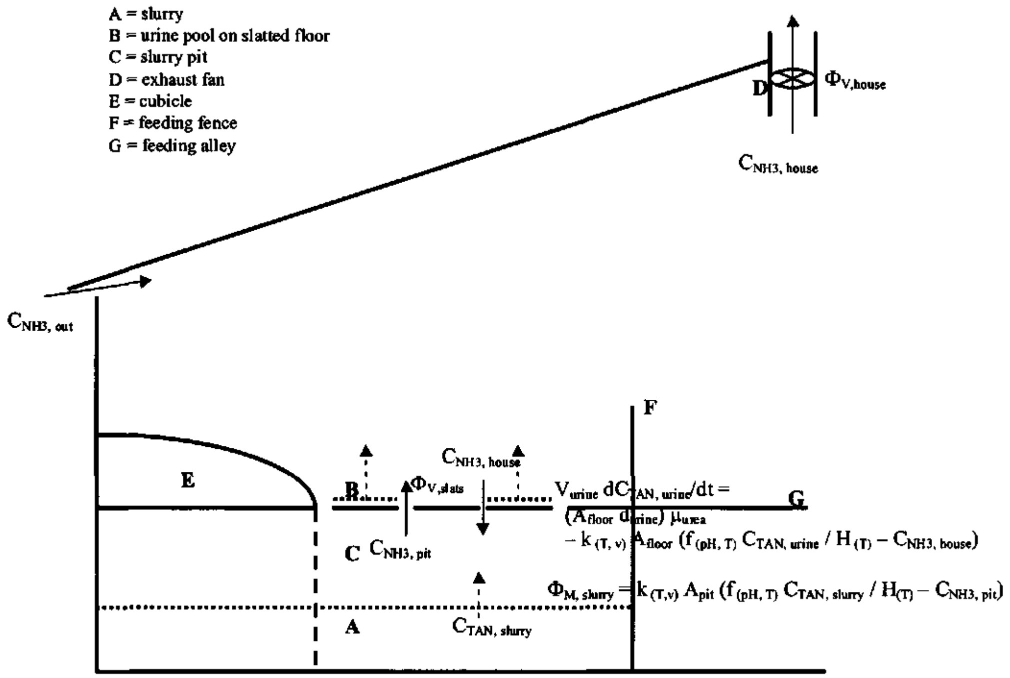


Figure 6.1: Schematic representation of the mass balances for urine pools (upper) and the slurry (lower) in the improved NH_3 emission model for cubicle dairy cow houses. Mass balance subscripts refer to the location in the house, whereas the variable parameters are expressed as subscripts between parentheses. Dashed arrows indicate mass flux of NH_3. Solid arrows relate to air flow.

2.1 Ammonia mass balance of the slurry pit air

The NH_3 emission from the pit was calculated as the product of the air exchange through the slatted floor ($\Phi_{V,\ slats}$) and the concentration of NH_3 in the pit air ($C_{NH3,\ pit}$). The air exchange rate through the slatted floor ($\Phi_{V,slats}$; Equation 6.1) was modeled as a function of the difference (ΔT) in temperature of air in the pit (T_{pit}) and the outside air (T_{out}) and the ventilation rate of the cow house (VR, in % of maximum ventilation rate). This equation was based upon a separate study conducted in the same cow house (Monteny *et al.*, 2000b):

$$\Phi_{V,\ slats} = Y + Z\ \Delta T \qquad [6.1]$$

Values for Y (intercept) and Z (slope) at various values for VR are summarized in Table 6.1. The table also contains adapted parameter values, to account for the possible overestimated air exchange rates at lesser and negative temperature differences, as indicated by Monteny *et al.* (2000b). The adaptations were a 50% lesser air exchange rate at air exchange rates of or below 0 °C and a linear increase with temperature difference to the same air exchange rates at temperature differences of 10 °C.

Table 6.1: Values for the intercept (Y) and the slope (Z) of air exchange rate through the slatted floor as a function of difference in temperature between air in the pit and outside air at different ventilation rate (Basic values derived from Monteny et al., 2000b).

VR in % of maximum (in $m^3\ h^{-1}$ per animal place)	Y ($m^3\ h^{-1}$)		Z ($m^3\ h^{-1}\ {}^{\circ}C^{-1}$)	
	Basic	Adapted	Basic	Adapted
50 (375)	1426	713	274	345
75 (560)	1547	773	572	649
100 (750)	2299	1149	536	651

The NH_3 concentration in the pit air was calculated with the following mass balance:

$$V_{pit}\frac{dC_{NH3,pit}}{dt} = \Phi_{M,slurry} - \Phi_{V,slats}\,(C_{NH3,pit} - C_{NH3,house}) \qquad [6.2]$$

with:

V_{pit} = volume of air in the pit (m^3)
$dC_{NH3,pit}/dt$ = change in NH_3 concentration in the pit air ($kg\ N\ m^{-3}\ s^{-1}$)
$\Phi_{M,\ slurry}$ = mass flux of NH_3 (production) from slurry ($kg\ N\ s^{-1}$)
$\Phi_{V,slats}$ = air exchange rate through the slatted floor ($m^3\ s^{-1}$)
$C_{NH3,pit}$ = NH_3 concentration in the slurry pit air ($kg\ N\ m^{-3}$)
$C_{NH3,\ house}$ = NH_3 concentration in the house = exhaust air ($kg\ N\ m^{-3}$)

The component $\Phi_{M,\ slurry}$ was calculated with the NH_3 production module for the pit in the 1998 model (see Figure 6.1). Acting variables for the mass transfer coefficient (k) are the air velocity in the pit (v_{pit}) and the slurry temperature (T_{slurry}). The latter variable is also acting on the fraction of free NH_3 (f) and Henry's constant (H). Moreover, the pH of the slurry top layer is acting variable ($pH_{slurry,\ top}$) for f. Other input parameters are the surface area of the slurry pit (A_{pit}) and the TAN concentration of the slurry top layer ($C_{TAN,\ slurry}$) (Monteny *et al.*, 1998). Results of a study of the development of urine pH after application on a floor and slurry (Monteny *et al.*, 2000a) was used to relate the pH of the top layer of the slurry to the initial pH of the urine ($pH_{urine,\ t=0}$):

$$pH_{slurry,\ top} = pH_{urine,\ t=0} + 0.5 \qquad [6.3]$$

Values of the acting variables and the other input parameters were directly measured.

2.2 Ammonia mass balance for the cow house air

The total NH_3 emission from the cow house was calculated as the product of the ventilation rate of the house ($\Phi_{V,\ house}$) and the NH_3 concentration in the ventilated air ($C_{NH3,\ house}$). The following mass balance Equation 6.4 for the air inside the house was used to calculate $C_{NH3,\ house}$:

$$V_{house}\frac{dC_{NH3,house}}{dt} = \Phi_{V,slats}\,(C_{NH3,pit} - C_{NH3,house}) + \Phi_{M,floor} - \Phi_{V,house}(C_{NH3,house} - C_{NH3,outside}) \qquad [6.4]$$

with:

$\Phi_{M,\,floor}$ = mass flux of NH_3 (production) from the urine pools on the floor (kg N s^{-1})

$\Phi_{V,\,house}$ = measured air exchange rate of the cow house ($m^3\ s^{-1}$)

$C_{NH3,house}$ = NH_3 concentration in the exhaust air (kg N m^{-3})

$C_{NH3,outside}$ = NH_3 concentration in the outside air (kg N m^{-3})

V_{house} = volume of the cow house (m^3)

$dC_{NH3,\,house}/dt$ = change in ammonia concentration in the air inside the house = exhaust air (kg N $m^{-3}\ s^{-1}$)

The component $\Phi_{M,\,floor}$ was calculated with the TAN mass balance for urine pools on the slatted floor in the 1998 model (see Figure 6.1). Input parameters for urea conversion (μ_{urea}) are urease activity (μ_{max}), Michaelis-Menten constant (K) and urea N concentration (C_{urea}). The floor temperature (T_{floor}) is the acting variable for the mass transfer coefficient (k), the fraction of unionized NH_3 (f) and Henry's constant (H). The coefficient k has also the air velocity at floor level (v_{floor}) as acting variable. The pH of the urine on the floor (pH_{floor}) is also acting variable for f.

The urination behavior is modeled with the parameters urination frequency (uf), slatted floor area (A_{floor}), floor area covered per urination (A_{pool}: 0.8 m^2), and depth of the urine pools on the floor (d_{pool}: 0.00048 m) are input parameters. The latter two values are defaults for slatted floor and used to calculate the volume of each urine pool (V_{urine}).

Air velocity could not be measured, because of the presence of animals. The following equation was assumed, relating v_{floor} to VR:

$$v_{floor} = 0.1 + VR*0.0015 \qquad [6.5]$$

Instead of a constant, pH_{floor} was modeled as (Monteny *et al.*, 2000a):

$$pH_{floor} = A + B\,e^{-kt} + C\,t \qquad [6.6]$$

with:

A, B, C = constants

e^{-k} = exponential development component (k = 0.2627)

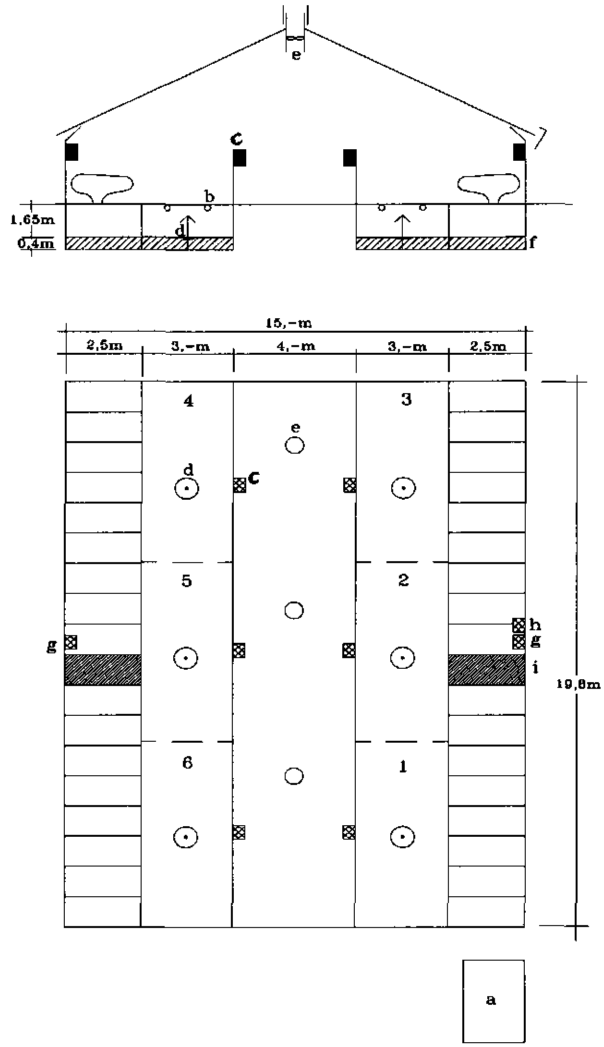
t = time (h)

This equation was derived from laboratory experiments with dairy cow urine applied on floors and slurry in a temperature range of 5-15 °C. The $pH_{urine,\,t=0}$ is represented by A + B, and was measured in this experiment. The values of B (-1.1) and C (-0.002) were taken from Monteny *et al.* (2000a). The other acting variables and input parameters were directly measured in the current experiment.

2.3 Measurements and observations

Model input data were collected in the same dairy cow house as described by Monteny *et al.*, (1998) during three experimental periods of seven to eight days each, distributed over the year 1997. The reasons for this were to ensure a wide range of climatic conditions and to crease independent data sets for the model validation.

A plan and cross-section of the cow house is presented in Figure 6.2. Climatic data (temperatures, air velocity), NH_3 concentrations and air exchange rates were measured in an eight minute cycle. All other variable input data were collected on the day prior to the start of each experimental period and assumed to be valid for that period.



a = measurement shelter
b = pit air sampling system
c = connection point per sector (1 ...6) for pit air, including convertor
d = steel bar with cover holding temperature and air velocity sensors
e = fans
f = layer of slurry
g = points for outside air sampling, incl. convertor
h = collection point for indoor air sampling (air from 3 fans), incl. convertor
i = concentrate dispenser
k = measurement shelter

Figure 6.2: Plan and cross section of the mechanically ventilated cubicle house for dairy cows in Duiven.

The experimental periods were chosen to obtain maximal variation in external conditions (mainly outside air temperature) that are relevant for the emission of NH_3. Two VR levels were operated during each experimental period (Table 6.2).

Table 6.2. Experimental periods, sub periods and ventilation rates.

Experimental periods and sub-periods	VR (%)	Beginning and end
1 – a	50	14 March 10:00 – 18 March 10:00
1 – b	75	18 March 10:00 – 22 March 10:00
2 – a	50	10 May 14:00 – 13 May 20:00
2 – b	75	13 May 20:00 – 17 May12:00
3 – a	75	13 October 13:00 – 17 October 09:00
3 – b	100	17 October 09:00 – 20 October 09:00

2.4 Dairy cow house

The measurements and observations were conducted in a dairy cow house with two rows of 17 cubicles each, two 3 m wide slatted floors (A_{floor}: 127 m^2) and a 3 m wide central feeding passage. Urease activity (μ_{max}) was measured on eight locations in the middle of the slatted floor of each alley with a method described in detail by Braam and Swierstra (1999). In brief, μ_{max} was calculated from the amount of TAN produced in the first 30 minutes from a 50 mL sample containing a 10 mg L^{-1} urea solution in a bottomless cylinder resting upon the slatted floor. Mean μ_{max} was calculated by averaging urease activities per location.

A 1.65 m deep slurry pit (A_{pit}: 184 m^2) was located under the slats and cubicles. The slurry level in the pits was lowered to 0.4 m above the pit floor at the beginning of each experimental period, resulting in a V_{pit} of 230 m^3. This value was used as a constant in spite of the increase of the slurry level by 0.01 m per day due to urine and feces production by the cows. Steel bars were erected and fixed at equal distance to the bottom of the pits at three locations in each slurry pit (six in total). Each bar held a sensor (Schmidt SS) for measurement of v_{pit} and sensors (AD 592cN) for T_{pit} and T_{slurry}. The T_{pit} and v_{pit} sensors were positioned at 1.0 m above the pit floor. The T_{slurry} sensors were attached to square poly styrene floaters. The bars were covered with a steel hat to protect the sensors from getting covered by feces and urine from above.

Six AD 592cN sensors were integrated in the top of the slatted floor to measure T_{floor}. Inside air temperature (T_{house}) and T_{out} were measured with Rotronic Hygromer i100 sensors. All sensors were calibrated before and after the experiment.

The cow house (V_{house}: 1,300 m^3) was mechanically ventilated. Three fans (Fancom type 1450T; capacity: 8,000 m^3 h^{-1} each) were placed in the exhaust shafts, positioned at equal distances along the ridge of the roof. Air entered the building through a space-boarded inlet system at the lateral sides of the building. Inlet widths were fixed at 0.02 m during the experiments. The actual air exchange rate of the house ($\Phi_{V,\ house}$) was measured by a pulse counter on fanwheel anemometers, placed in the exhaust shafts, directly under the fans. The relationships between the number of pulses from the anemometer and the air exchange rate were determined in a wind tunnel.

2.5 Cows and management

Thirty-two lactating cross-bred Holstein Friesian cows were present in the house during the whole experiment. They were milked twice daily, between 5:30 and 6:00 h and between 15:30 and 16:00 h, in a separate milking parlor. As a consequence, no animals were present in the house during those times. In the model this was accounted for by assuming a daily urine production period of 23 hours. The diet composition and average daily intake by the herd is presented in Table 6.3.

Table 6.3: Composition of the diet and mean daily intake per animal.

Experimental period	Diet components	Daily intake (kg per animal)
1	Grass silage	14.1
	Maize silage	23.4
2	Grass silage	3.9
	Maize silage	20.3
	Structure mix	7.0
	Protein concentrate	1.9
	Straw	1.9
3	Grass silage	29.7
	Maize silage	6.3

The diet during period 2 was caused by a shortage of grass silage, which was compensated by three additional components. Additional concentrates were fed in an automatic concentrate feeding box during all periods; the amount of concentrates depended on the individual milk yield.

The following diet related data were determined at the day prior to the start of the experimental periods: urine composition, urination frequency and slurry composition.

The parameters C_{urea} and $pH_{urine,t=0}$ were measured in a defrosted mix sample of urine collected in each experimental period during four sessions of two to three hours distributed over the day (Smits *et al.*, 1998): 5:00-7:00 h; 8:00-10:00 h; 15:00-17:00 h; 18:00-21:00 h. During each session, as many urinations (on average 80 for each set of four sessions) as possible were sampled with a 1.0 L pan. The urine was subdivided into 100 mL flasks and immediately placed in a cooling box with ice blocks. At the end of each session the flasks were stored in a freezer (-18 °C).

Urination frequency (uf) was measured with video equipment. The video observations ran for 24 hours per experimental period. Due to technical failure, reliable data on the urination frequency were only available for period 1.

In each pit, the top layer of the slurry was sampled at three locations. The samples were collected in 1.0 L pans, mixed and analyzed for $C_{TAN,\,slurry}$ and pH_{slurry}.

2.6 Ammonia concentrations and emission

Ammonia concentrations were measured in the air inside the pit ($C_{NH3,\ pit}$) , the outside air ($C_{NH3,\ out}$) and the exhaust air ($C_{NH3,\ house}$). The pit air was continuously sampled through teflon tubes at 48 points positioned directly beneath the slatted floor and equally distributed of the six sections (Figure 6.2). A mixed sample of the air extracted from each section was made in collection units attached to the feeding fence. Outside air sampling points were located in the air inlet (one point in the middle of each inlet, representing incoming air). Indoor air was sampled in the exhaust (three points; one for each ventilation shaft). Air samples were separately mixed in units fixed at the lateral wall of the cow house. All mixing units contained a stainless steel convertor, where NH_3 was converted to NO_x at 775 °C. Air from the mixing units was drawn by a pump through insulated and heated FEP tubes through a 6+6-channel multiplexer. Sets of two multiplexer valves were sequentially opened and air was drawn to a two-channel NO_x analyser (Thermo Environmental Instruments Inc., model 48). The analyser was calibrated before and after each experimental period. One measurement cycle, with a concentration measurement for each mixing unit, took eight minutes.

The NH_3 emission from the pit was calculated as the product of $\Phi_{V,\ slats}$ (Equation 6.1) using the adapted parameter values and the difference between the measured means values of $C_{NH3,\ pit}$ and $C_{NH3,\ house}$.

2.7 Model evaluation

For each sub period (fixed VR; Table 6.1), the quality of the slurry pit module was judged by comparison of the calculated (Equation 6.2) and measured $C_{NH3,\ pit}$. Furthermore, the calculated (Equation 6.4) and the measured NH_3 emission from the cow house were used as quality for judging the validity of the whole model. A regression analysis was performed for each sub period, with the hourly mean values of pit air concentration and emission from the house as independent data, to analyze the stability of the model for different levels of VR.

3 Results

3.1 Model parameters

Table 6.4 contains the values of the variable model input data for each experimental period. At the pH values of the fresh urine ($pH_{urine,\ t=0}$ 8.5), $pH_{slurry,\ top}$ would be 9.0 for all periods according to Equation 6.3. This equation appeared to be valid for period 1, whereas a factor of 0.3 (resulting in a $pH_{slurry,\ top}$ of 8.8) was also used in the simulations for periods 2 and 3. This assumption was based upon the difference in diets (Table 6.2) and the results of the slurry analysis.

Initial model runs using T_{slurry} resulted in poor dynamics of the NH_3 concentration in the slurry pit. The temperature measured was apparently not representative for the urine layer on top of the slurry because the location of the sensors may have been too deep in the slurry. As an alternative, T_{pit} was used simulate the processes in the urine layer present upon the slurry and improved simulation results were obtained.

Table 6.4: Variable model parameters (variation between parenthesis) and values for each experimental period.

Parameter (unit)	Experimental period		
	1	2	3
Urease activity (10^{-3} kg N m^{-3} s^{-1})	1.3 (0.6-1.9)	1.4 (0.6-2.4)	1.5 (1.1-2.1)
Urea nitrogen concentration (mg N l^{-1})	5.2 (4.8-5.4)	3.8 (3.6-4.2)	3.5 (3.4-3.6)
Urination frequency (cow^{-1} day^{-1})	9	*	*
TAN concentration slurry (g N kg^{-1})	1.31 (1.01-1.78)	1.79 (0.90-2.41)	1.50 (1.32-1.61)
Air velocity in pit (m s^{-1})	*	*	Equation 6.7
Air velocity on floor level (m s^{-1})	← **; Equation 6.5 →		
Temperature of slurry top layer (°C)	←Temperature of air in the pit →		
Floor temperature (°C)	←Measured →		
pH of urine on floor (-)	←Equation 6.6 →		
pH of urine on slurry (-)	Eqn.6.3 (pH = 9.0)	pH = 8.8	pH = 8.8
pH of slurry top layer (-)	7.9 (7.6-8.4)	7.2 (7.0-7.3)	7.8 (7.6-8.2)
pH of urine produced (-)	8.5 (8.4-8.6)	8.5 (8.4-8.6)	8.5 (8.4-8.6)

** = measurements and observations unsuccessful; ** = measurements not performed*

In spite of the steel hats, the sensors appeared to be fouled by feces and urine within a couple of days and no reliable data of v_{pit} were recorded for periods 1 and 2. During summer grazing after the slurry level in the pits was lowered, between periods 2 and 3, larger steel hats were installed, resulting in a reliable set of air velocity data. Figure 6.3 presents v_{pit} against the difference in temperature between outside air and air in the pit (ΔT).

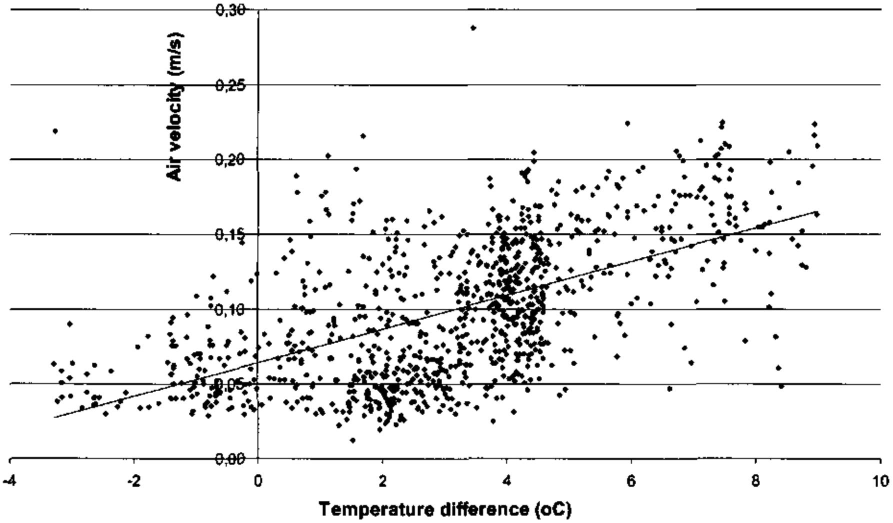


Figure 6.3: Air velocity in the pits against difference in temperature between outside air and pit air during experimental period 3. The line represents the linear trend line.

Although the data in figure 6.3 show great variability, the following equation was derived for the air velocity in the pit for $\Delta T > 0$ ($0.05\ m\ s^{-1}$ for $\Delta T < 0$):

$$v_{pit} = 0.05 + 0.015 * \Delta T \qquad (R^2 = 0.32) \qquad [6.7]$$

3.2 Model performance

The effect of the adapted pH values for the slurry pit (periods 2 and 3) and air exchange rate through the slatted floor (all periods) on the model performance is illustrated by Figure 6.4, presenting the measured and calculated NH_3 concentration of the slurry pit air for sub-period 3b.

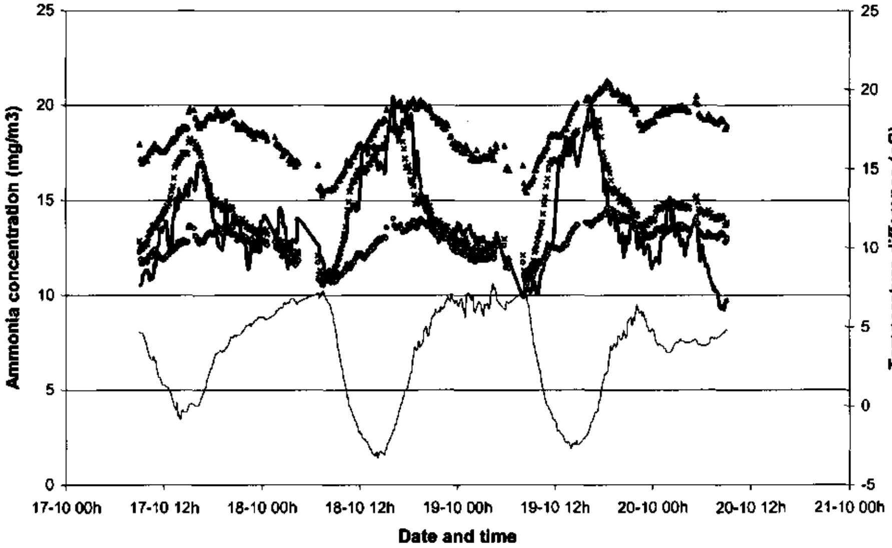


Figure 6.4: Mean measured (bold line) and calculated ammonia concentration (marker) of the air inside the slurry pit during the experimental sub-period 3b (VR 100%), with a pH of the slurry top layer of 9.0 (Δ) and 8.8 (o), respectively, and with adapted values for the air exchange rate through the slatted floor (+). Temperature difference between the pit air and the outdoor air is represented by the slim bottom line.

At a $pH_{slurry,\ top}$ of 9.0, the calculated NH_3 concentration was much greater than the measured concentration. The model, with the original air exchange parameters (Table 6.1), performed better at a pH of 8.8 was used. The build up of NH_3 concentration was underestimated at small and negative temperature differences, mostly occurring around noon. The model performance greatly increased when the adapted air exchange rate parameters (Equation 6.1) were used. This illustrates the overestimated air exchange rate through the slatted floor in situations of stratified pit air. The adapted air exchange rate parameters (Table 6.1) were used in the further simulations.

The measured and predicted NH_3 concentrations of the slurry pit air and the measured and calculated NH_3 emission from the cow house for the three periods are presented in Figure 6.5a, 6.5b and 6.5c, respectively.

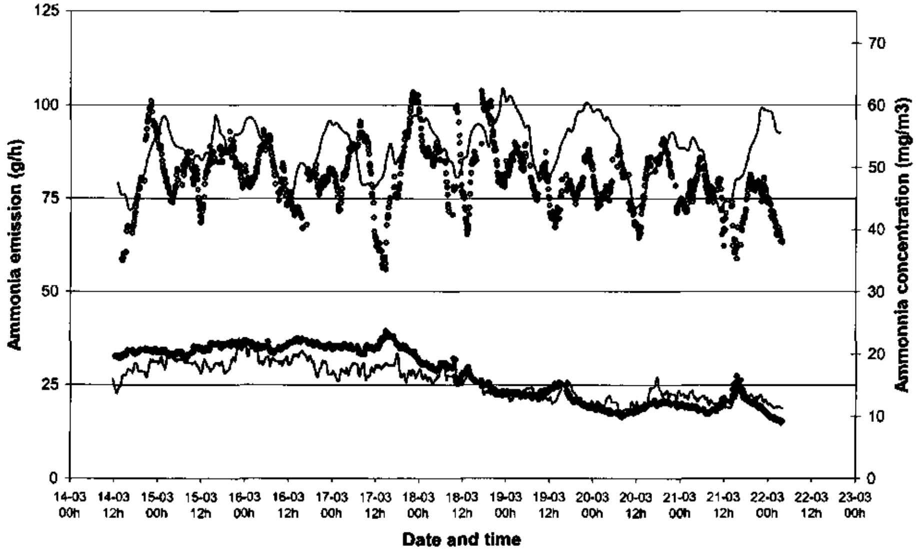


Figure 6.5a: Measured (lower line) and calculated (lower bold marker) ammonia concentration of the slurry pit air and the measured (upper line) and calculated (upper open marker) ammonia emission from the dairy cow house for experimental period 1.

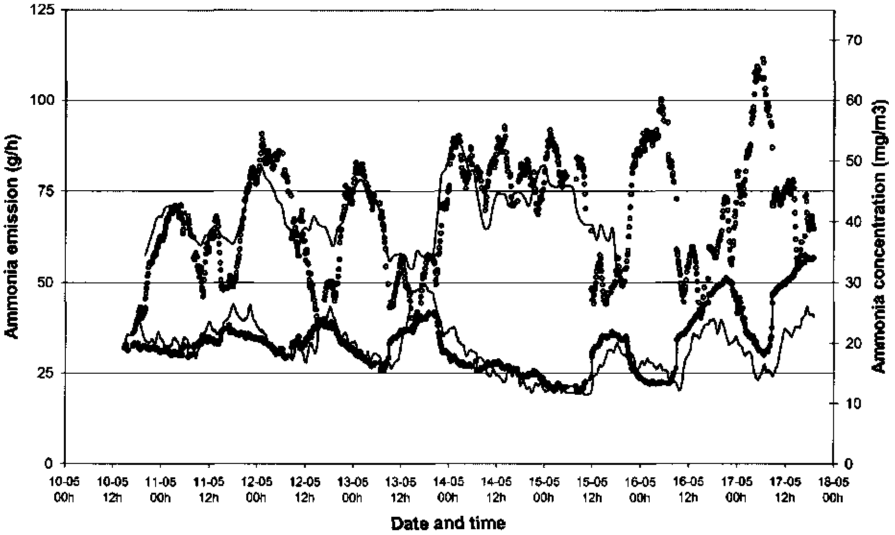


Figure 6.5b: Measured (lower line) and calculated (lower bold marker) ammonia concentration of the slurry pit air and the measured (upper line) and calculated (upper open marker) ammonia emission from the dairy cow house for experimental period 2.

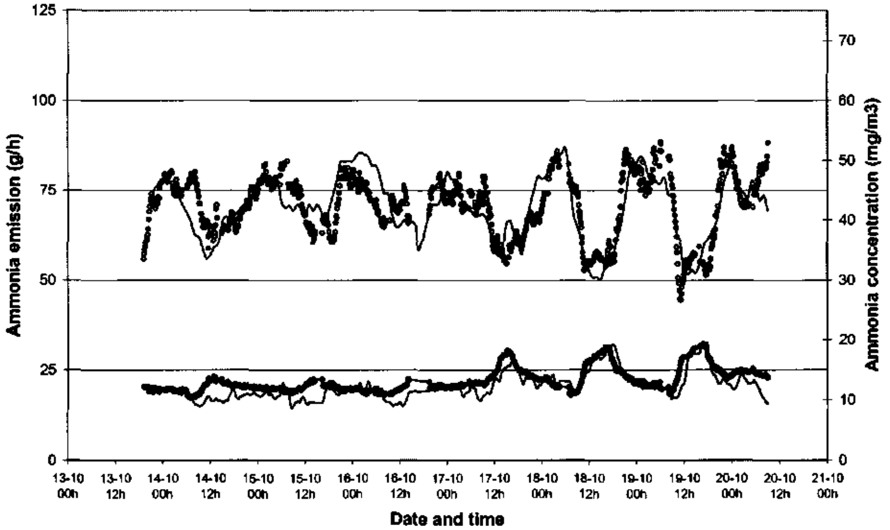


Figure 6.5c: Measured (lower line) and calculated (lower bold marker) ammonia concentration of the slurry pit air and the measured (upper line) and calculated (upper open marker) ammonia emission from the dairy cow house for experimental period 3.

Based upon visual analysis of the results in these figures, the model performance was satisfactorily, both under relatively static (period 1 and sub-period 3a) and fluctuating (period 2 and sub-period 3b) climatic conditions.

The regression analysis performed per period showed that the parameters (intercept and slope; Table 6.5) differed significantly ($P<0.01$) for the levels of VR per experimental period. This indicates that the model responded differently to changes in VR or that VR related parameters (e.g. v_{pit} and v_{floor}) were not adequately modelled. Moreover, the model performed differently for each of the experimental periods. This may have been caused by (small) fluctuations in model parameter values (e.g. $pH_{slurry, top,}$, $pH_{urine\ t=0}$, $C_{urea,}$) between the (sub-)periods, whereas constant values were assumed for each experimental period. In general, differences between the model calculation and the measurements may have been due to a different reaction of the model to parameters that were related to the ventilation rate of the house (e.g. v_{floor}) or to parameters that were not taken into account by the emission model (assuming correct measurements). Best model performance, i.e. a slope of around 1 and intercept near 0, was observed in situations with the greatest fluctuations (e.g. NH_3 concentration in sub-periods 1b, 2b and 3b and emission in sub-period 2a). Poor results of the regression analysis were at least partly caused by differences in response time between the model and the measurements. Figure 5c illustrates this, where both shorter (e.g. between 15 October 12:00 and 16 October 12:00) and longer intervals occurred between two successive minimum emission levels for the model compared to the measurements. Slight differences in concentration and emission levels were also observed (e.g. for sub-period 1a).

Table 6.5: Percentage of variance accounted for per period (R^2) and regression parameters per sub period.

	Ammonia concentration in the pit			Ammonia emission from the house		
Period	Intercept	Slope	R^2	Intercept	Slope	R^2
1			93.4			10.5
1a	13.59	0.40		49.2	0.37	
1b	-0.40	0.99		62.7	0.28	
2			61.9			44.2
2a	9.9	0.48		- 2.0	0.97	
2b	- 2.2	1.27		48.0	0.37	
3			76.9			48.5
3a	12.1	0.0		55.3	0.23	
3b	4.6	0.72		24.0	0.65	

3.3 Ammonia fluxes

Figure 6.6a through 6.6c show the measured NH_3 flux (emission) from the cow house and the calculated flux from the pit for periods 1, 2 and 3, respectively.

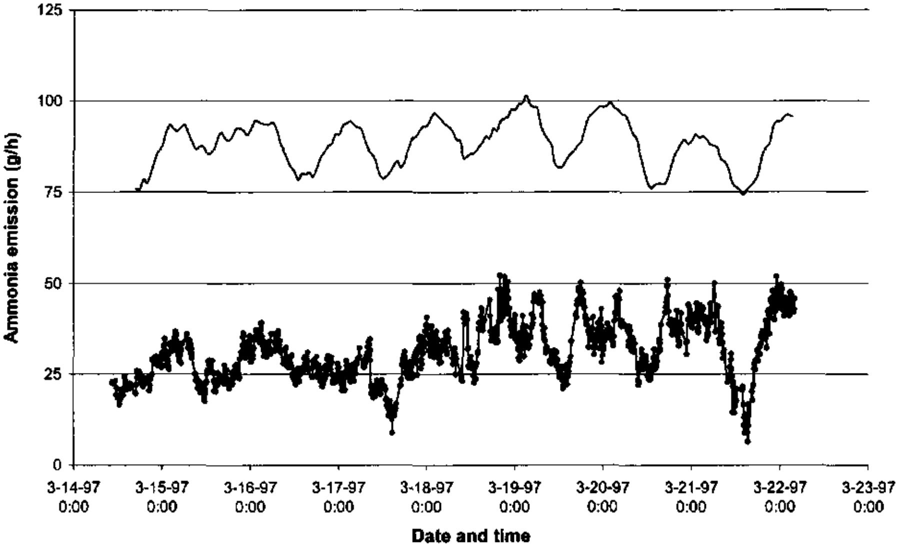


Figure 6.6a: Measured ammonia flux from the cow house (upper line) and calculated ammonia flux from the slurry pit (lower line with marker) for experimental period 1.

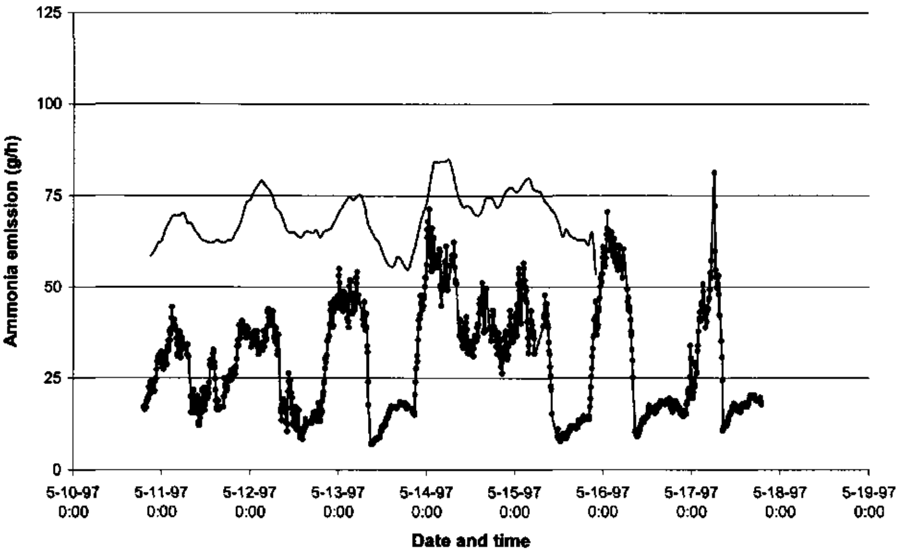


Figure 6.6b: Measured ammonia flux from the cow house (upper line) and calculated ammonia flux from the slurry pit (lower line with marker) for experimental period 2.

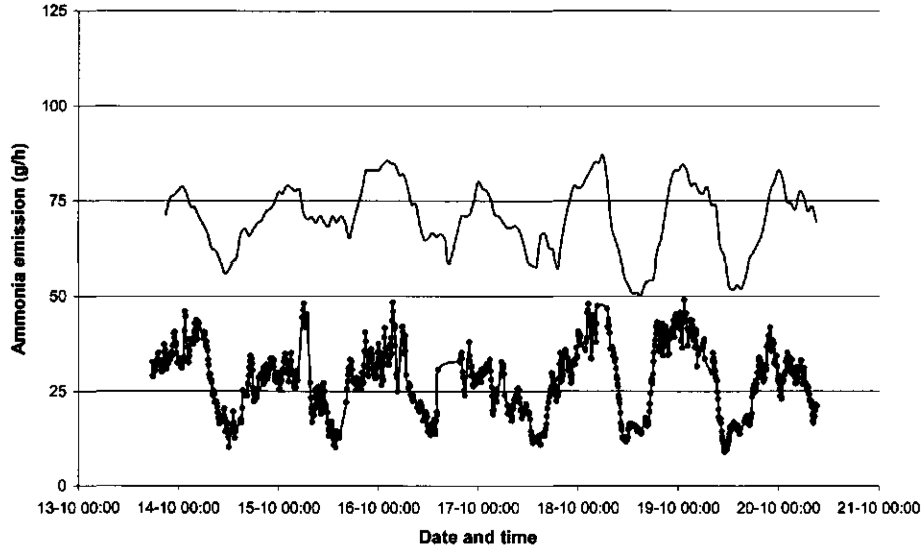


Figure 6.6c: Measured ammonia flux from the cow house (upper line) and calculated ammonia flux from the slurry pit (lower line with marker) for experimental period 3.

These figures demonstrate that the pit contributes on average for 25% (sub-period 1a) to 40% (sub-period 1b, sub-period 3b) to the flux from the house. However, momentary pit flux may account for over 80% of the emission from the house, as can be observed during period 2 (e.g. on May 14 around midnight). The results from period 3 in particular illustrate that the course of the NH_3 flux from the cow house greatly coincided with the fluctuations in the slurry pit flux and thus with the difference in temperature between the outside air and the air inside the pit. The greatest flux from the pit occurred at night when relatively cold air enters the pit through the slatted floor, causing great air exchange rates (Table 6.1) and air velocities (Figure 6.3). The latter results in a large NH_3 production from the urine on the slurry top layer, because the NH_3 mass transfer is positively related to the air velocity.

4 Discussion

4.1 Data quality

The main goal of the experiments was to present and validate an improved model for the emission of NH_3 from cubicle dairy cow houses, with the potential of separately calculate the emission from the floor and the underfloor pit. An intensive measurement program was conducted to achieve this. Still, problems occurred with the air velocity measurements and simplistic equations had to be used, especially for the air velocity at floor level.

Equation 6.7 for the air velocity in the pit was based upon one series of measurements (Figure 6.3). In spite of a great deal of variation and a potential effect of the steel hats (not tested), the air velocity tended to increase with the temperature difference between pit air and outside air. An independent validation for Equation 6.7 can be derived from the data for the air exchange through the slatted floor (Table 6.1). Assuming that the volume of exchanged air flows horizontally through the pit (total vertical plane of the pits is 7.2 m^2), air velocities would be 0.03-0.06 $m\ s^{-1}$ (adapted and basic values of Y) for negative temperature differences and 0.16 $m\ s^{-1}$ at a temperature difference of 10 °C. These values are of the same order of magnitude as the results of Equation 6.7. Furthermore, air velocity appears to be above 0.02 $m\ s^{-1}$ even at negative temperature difference where values of 0 would be expected. This was most likely due to sensor inaccuracy at low air velocities.

Monteny *et al.* (1998) used an indoor temperature dependent linear relationship for the air velocity at floor level, basically because the air exchange rate of the house was related to the indoor air temperature. In the current experiment, however, air exchange rate was kept constant during each of the experimental sub-periods.

4.2 Model quality

The model performed well using an extensive set of data derived from measurements and observations. The model appeared to be extremely sensitive to pH. Adjusted pH values for the top layer of the slurry had to be used to obtain a good fit for periods 2 and 3. Results from the slurry analysis (pH 7.2 for period 2 against pH 7.9 for the other periods) supports the lesser pH value for the pit in period 2 and may have been related to the change in diet (Table 6.3). Moreover, Monteny *et al.* (2000a) demonstrated that the level of pH development in urine applied on slurry is affected by the slurry pH. Still, the slurry pH data for period 3 would no support the reduced pH for urine on slurry, demonstrating the complexity of the pH matter in emission modelling.

The slurry pit mass balance performed well, although adapted values had to be assumed for the air exchange rate at negative temperature differences. Monteny *et al.* (2000b) already discussed the possibility of having over estimated the air exchange rate at less and negative temperature differences. Diffusion of the tracer gas used for measurement of the air exchange rate and local losses of the tracer gas due to animal locomotion and deposition of urine and feces may have caused this. These effects will have had the greatest effect at lesser air exchange rates (and thus great gas concentrations in the pit air). The results from the current model predictions show that the suggested correction may have been realistic.

The total surface area of the slurry pit was used as input for Equation 6.2 and the NH_3 concentration in the pit air was assumed to be representative for the whole pit air volume (connected sections directly below the slatted floor and beneath the cubicles), thus assuming complete mixing. For technical reasons, the NH_3 concentration measurements could only be carried out for the section directly below the slatted floor and the measured NH_3 concentrations were assumed to be valid for the section below the cubicles too. The open construction of the slurry pit sections in the cubicle house used in this study allows this and will also be valid for the situations where air flow in both pit sections is not hindered by pit construction elements (e.g. pit walls). When the model is used for situations with pit sections that are not connected, only the slurry surface area and pit volume directly beneath the floor has to be used as model input.

4.3 Using the improved model in practice

The improved NH_3 emission model was validated under research conditions in a mechanically ventilated dairy cow house. Although the model performed well during three independent experimental periods, application of the model in practical situations, e.g. in a naturally ventilated cubicle house, needs to be validated separately, Realistic data on diet (urine and slurry composition, including pH) and indoor climate are usually not present in practice. Data on urine and slurry composition are necessary as input and need to be known to run the model. The equations used for the pH (Equations 6.3 and 6.6), although applicable, may have to be validated through either pH measurements or by means of a calibration measurement of the emission from the house *in-situ*.

The model has potential as a tool for comparative assessment of separate mitigation strategies for NH_3 emission from the underfloor slurry pit and the floor. The results presented in Figures 6.5a through 6.5c show that improved mixing of incoming (outside) air with air inside the house, resulting in less fall of cold air, will not only reduce the air exchange through the slatted floor (Equation 6.1; Table 6.1 and Monteny *et al.*, 2000b), but also the air velocity in the pit. As a consequence both the NH_3 volatilization and the pit emission are reduced. Moreover, different floor systems with a drastically reduced surface area for air exchange, simulated by stagnant pit air conditions (e.g. on May 14 and October 18 and 19; Figures 6.5b and 6.5c) may substantially lower the emission from the house. This is confirmed by Braam *et al.* (1997), who demonstrated that the emission level from a cow house with covered pit openings was much lower and relatively unaffected by temperature difference between inside air and outside air. Because of the great influence of the pit emission on the variation in NH_3 emission from the house (Figures 6.6a, b, and c), measures that reduce the pit emission will also result in a less fluctuating emission from the house. This could benefit the development of adapted and less intensive measurement protocols for NH_3 emissions from housing systems equipped with measures that reduce the pit emission.

5 Conclusions

1. A mechanistic ammonia emission model with separate ammonia nitrogen mass balances for the slurry pit of a cubicle dairy cow house is necessary to accurately and realistically predict the amount of and variation in the ammonia flux through a slatted floor.

2. Detailed information on the pH of urine present on the top layer of the slurry in the pits is necessary to assure the quality of the predicted ammonia emission from the slurry pit.

3. The slurry pit of a dairy cow house greatly contributes to the emission from the house.

4. The patterns of the ammonia emission from the pit and the house coincided to a great extent. Consequently, the ammonia emission from the cow house equipped with means that reduce the pit emission will fluctuate less.

Literature

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Monteny, G.J., D.D. Schulte, A. Elzing and E.J.J. Lamaker, 1998. A conceptual mechanistic model for the ammonia emissions from free stall cubicle dairy cow houses. *Transactions of the ASAE* 41 (1): 193-201.

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7

Challenging the model

1 Introduction

In the previous chapter, the model for simulation of the NH_3 emission from a mechanically ventilated dairy cow house was presented and used. The aim of this chapter is to demonstrate the potential of the model for the assessment of emission levels and emission reducing measures by comparing the results of simulations for two naturally ventilated cubicle houses for dairy cows with measured NH_3 emissions.

2 Validation on a commercial farm

The first cow house was commercially operated and located in the village of Wangen-Leupolz, near Stuttgart in southern Germany. The measurements results originated from a larger research conducted in 1997 with the goal to determine the gaseous emissions from a practical dairy cow house (Brose, 2000). Two comparable measurement periods were used for model simulations: period 1 (12-16 April) and period 2 (20-24 April). The dairy cow house and the experimental set up, including the measurement equipment, the diet, and the production results, are described in detail by Brose (2000). The most important aspects are summarized below.

2.1 Dairy cow house and management

During the research, 75 head of cattle were present in the cubicle house. A plan of the house is presented in Figure 7.1. A 2+1 row compartment housed 55 dairy cows; 20 heifers were kept in a one row compartment. Both compartments were only separated by a central feeding alley. The walking alleys for the animals were made of slatted floor elements (floor area 230 m^2). No scrapers were used. Faeces were abundantly present on the slatted floor, thus covering a substantial part of the slatted floor openings (Brose, personal communication). The remainder of the animal excreta was stored in a pit below the slatted floor. The pit (area 230 m^2; pit air volume 230 m^3) was connected by a slurry channel to an outside slurry lagoon. The cow house (volume 2,100 m^3) was naturally ventilated. Air entered through open ridges in the lateral sides of the house. The originally open ridge in the top of the roof was sealed. Outlet air left the building through seven chimneys with a total outlet area of 5 m^2.

2.2 Measurements and observations

The ventilation rate was measured with fanwheel anemometers placed in each chimney, by counting the number of rotations (pulses). The ventilation was between 15,000 and 20,000 m^3 h^{-1} (200-267 m^3 h^{-1} per animal). The NH_3 concentration of the exhaust air (seven locations), the incoming air (two locations) and the air beneath the slatted floor (one location) was measured by air sampling and analysis with an infrared spectrometer. Furthermore, indoor and outside temperature, and the temperature in the slurry pit were recorded. All data were stored on a PC as hourly mean values.

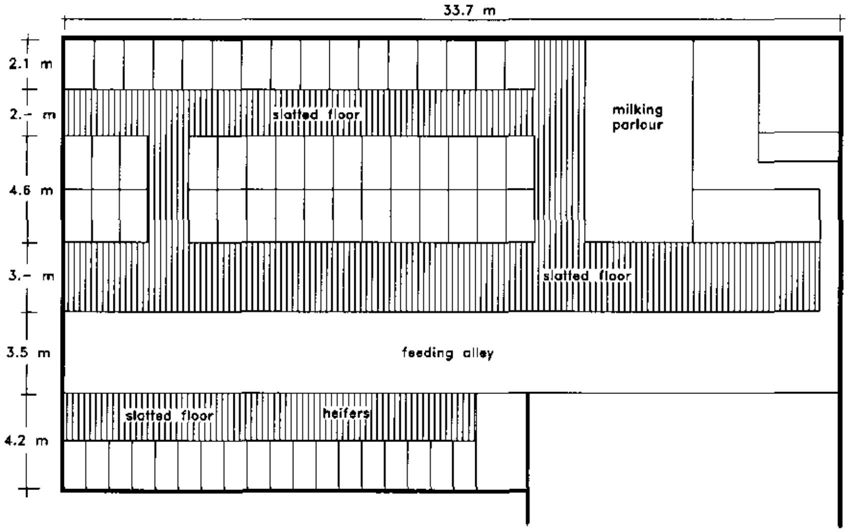

Figure 7.1: Plan of the naturally ventilated cubicle house for dairy cows in Wangen-Leupolz.

Because the measurements and observations were not intended to be used for model simulation and evaluation, input parameters for the model had to be estimated or were derived from the available information. Besides the geometrical parameters of the house and temperatures (see above), only the slurry composition (pH and concentration of total ammoniacal nitrogen, TAN) was determined. The pH was 7.1 for both periods. The concentration of TAN was 1.4 g L^{-1} and 1.6 g L^{-1} for period 1 and 2, respectively. The values of the site-specific variable parameters used for the simulations are presented in Table 7.1. All other parameter values were the same as in Table 3.1 (Page 44). The first period was used to calibrate the model. Period 2 was simulated with the calibrated model.

Table 7.1: Values of the variable parameters used for simulation of ammonia emissions from a commercial cubicle dairy cow house in Wangen-Leupolz during two periods in April 1997.

Parameter	Value	Comments
Urease activity (kg N m^{-3} s^{-1})	$0.27\ 10^{-3}$	Muck (1982)
Urination frequency per cow (day^{-1})	10	Estimated
Urea concentration of urine (UN; g N l^{-1})	4.5	Based upon a limited number of urine samples
Air velocity in the pit (m s^{-1})		← Equation 6.7 →
Air velocity at floor level (m s^{-1})	← Equation 6.5, with VR 100% equal to 20,000 m^3 h^{-1} →	
pH of urine on floor (-)	7.9	= pH_{faeces} + 1.4; see below
Depth of urine pools (mm)	1.0	Twice the value in Table 3.1
pH of slurry top layer (-)	8.4	= $pH_{slurry\ top}$ + 1.3; Chapter 4

The presence of faeces on the slatted floor was assumed to influence some of the floor related variables. The urease activity on the floor was replaced by the urease activity of faeces, with a values based upon Muck (1982). Furthermore, the depth of the urine pools left on the faeces was assumed to be double the depth of pools on clean slatted floors. Because no data were present on the pH of the urine, the pH of the urine present on the faeces (floor) was related to the pH of the faeces (pH 6.5; Brose, personal communication). The factor 1.4 was derived from unpublished results of measurements of the pH of urine applied on slurry, conducted in the framework of the experiments presented in Chapter 4 (Figure 7.2). The effect of the presence of faeces on the slatted floor on the air exchange through the slats was hard to quantify. To assess this, the results of the experimental work presented in Chapter 5 (Table 5.2; parameter values for all VR values) were adapted according to the procedure described in Chapter 6 (Table 6.1). Because the result of this analysis is valid for a clean slatted floor, a fitting procedure with the predicted and the measured NH_3 concentration in the pit air for period 1 was used to yield the equation for the faeces covered floor. In this procedure, the parameters in the equation for the clean slatted floor were reduced with the same percentage until the predicted and measured NH_3 concentrations in the pit air fitted. This resulted in the following equation for the Wangen-Leupolz cow house:

$$\Phi_{V,\,slats} = 250 + 160\ (T_{slurry\ pit} - T_{outside}) \qquad [7.1]$$

with:

$\Phi_{V,\,slats}$ = air exchange through the slatted floor ($m^3\ h^{-1}$)

$T_{slurry\ pit}$ = temperature of the air in the slurry pit (°C)

$T_{outside}$ = temperature of the outside air (°C)

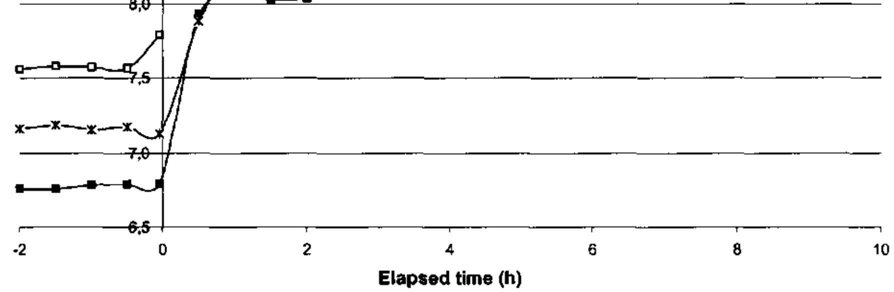

Figure 7.2: Increase in pH of urine after application on freshly collected dairy cow faeces at temperatures of 5 (replicates: ■ and □) and 15 ^0C (one experiment: ✱).

2.3 Results and discussion

The measured and calculated NH_3 emission from the house and NH_3 concentration of the pit air are presented in Figure 7.3 and Figure 7.4 for the first and the second measurement period, respectively. Mean measured NH_3 emission (42.5 and 37.3 g h^{-1} for period 1 and 2, respectively) were predicted satisfactorily: the respective calculated values were 35.3 and 34.9 g h^{-1}. The modelled fluctuations in NH_3 emission matched the measurements well, especially in period 2. The differences observed in period 1 could not be explained, but may be related to incidental events in the house.

These simulations demonstrate that detailed knowledge of the situation in the cow house is necessary to obtain realistic simulation results. In this specific case, some essential input parameters had to be derived from theory or other observations. The most uncertain was the influence of the presence of faeces upon the slatted floor on the air exchange through the slatted floor. Although based upon theory and procedures presented in this thesis, the validity of the adapted Equation 7.1 could not be tested. More information of the net slot area for air exchange would be needed to evaluate this approach.

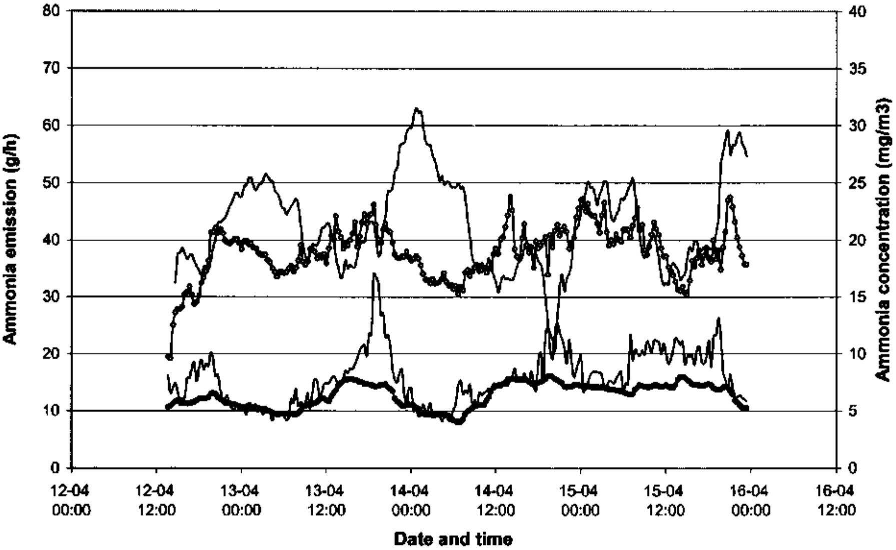

Figure 7.3: Measured (line) and calculated (marker) ammonia emission from the house (upper lines) and ammonia concentration (lower lines) in the pit air in a naturally ventilated dairy cow house in Wangen-Leupolz during the first period (calibration).

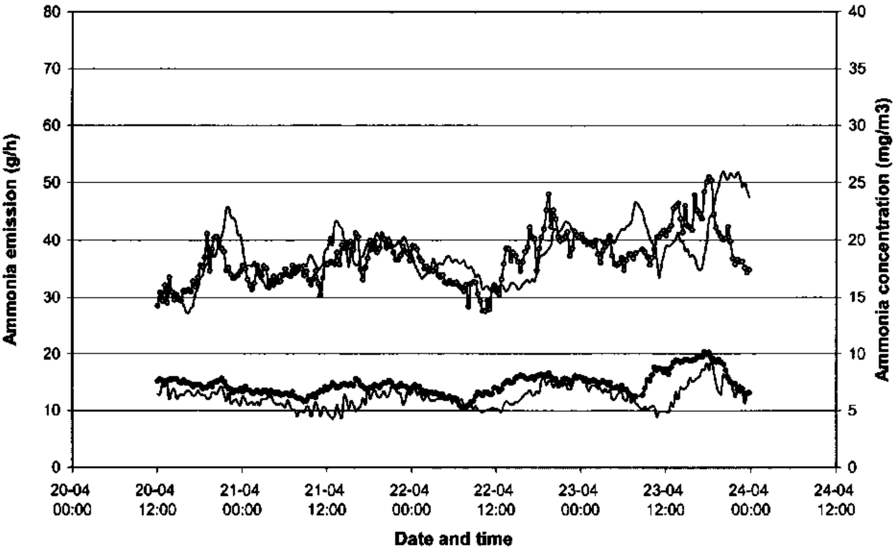

Figure 7.4: Measured (line) and calculated (marker) ammonia emission from the house (upper lines) and ammonia concentration (lower lines) in the pit air in a naturally ventilated dairy cow house in Wangen-Leupolz during the second period (validation).

3 Validation on an experimental farm with different diets

The naturally ventilated cow house at the experimental farm 'De Waiboerhoeve' in Lelystad, the Netherlands, was used for a research into the NH_3 emission reduction by different dairy cow diets. Additional data on the slurry and urine composition were collected to run the model. Model simulations were compared with measured NH_3 emissions.

3.1 Dairy cow house and management

The Lelystad cubicle house a naturally ventilated building with two rows of cubicles (34 and 31 cubicles) and a central feeding alley. During the research, 55-57 lactating cows were present. Young stock was housed in a fully separated compartment. The plan of the house is presented in Figure 7.5.

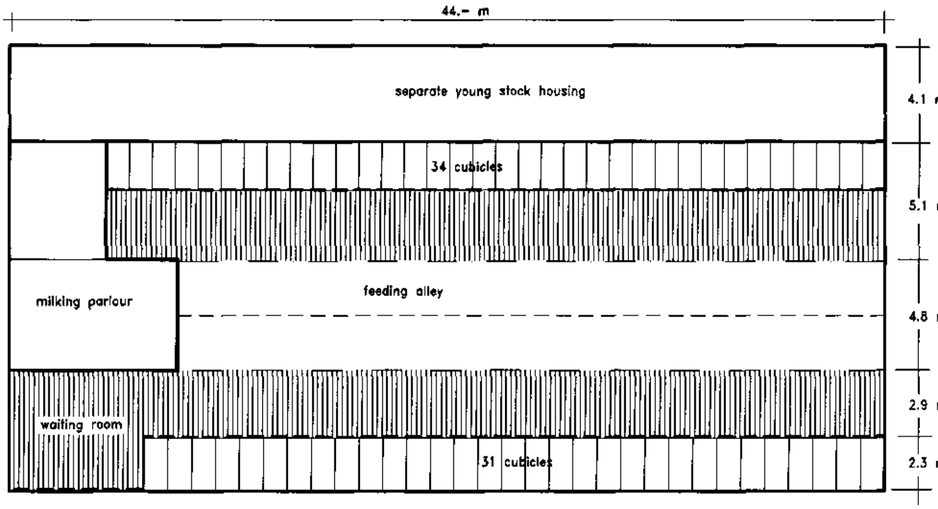

Figure 7.5: Plan of the naturally ventilated cubicle dairy cow house at the Waiboerhoeve, Lelystad.

The slatted floor area was 207 m^2. Slurry was stored beneath the slatted floor and the cubicles. The total surface area of the pits was 550 m^2. The diet treatments consisted of combinations of components, basically grass and maize silage, with a difference in the amount of rumen degradable protein (RDP). The RDP content of the diets was set at three levels: 0, 500, and 1.000 g d^{-1}. Each diet was administered during a period of three weeks. These periods were randomly distributed over the whole research period. The first two weeks of each period were regarded as transition periods. The measurements and observations were conducted in the third week of each period. Urine and slurry (top layer) sampling was conducted as described in Chapter 6.

3.2 Ammonia emission measurements

Ammonia emission was measured with a concentration ratio method using SF_6 (sulphur hexa fluoride) as a trace gas injected near the slatted floor. In brief, tracer gas injection points were attached to the separation boards of the cubicles and feeding fences to assure optimal distribution of the gas near the source of NH_3 emission. Air in the top of the building was sampled through a system with multiple openings, so a mix sample was obtained. This sample was analyzed for its concentration of NH_3 (convertor and NO_x monitor) and SF_6 (gas-chromatograph).

The source strength of NH_3, being the ammonia emission, was calculated with the following equation, assuming perfect mixing of NH_3 and SF_6:

$$MF_{SF6} : MF_{NH3} = C_{SF6} : C_{NH3} \qquad [7.2]$$

with:

MF_{SF6} = mass flux of the tracegas SF_6 injected near the floor (g h^{-1})
MF_{NH3} = mass flux of NH_3 (from floor and pit; g h^{-1})
C_{SF6} = concentration of the tracegas SF_6 in the exhaust air (mg m^{-3})
C_{NH3} = concentration of NH_3 in the exhaust air (mg m^{-3})

3.3 Input data for the simulations

The mean mass flux of NH_3 resulting from Equation 7.2, interpreted as NH_3 emission, was compared to simulations with the NH_3 production model presented in Chapter 3 (referred to as the 1998-model). The input data and their values per treatment are given in Table 7.2. This table contains data from 13 successive periods; only four treatments were replicated because the experiment was still on going.

Mean inside temperature varied between 4.3 (winter) and 21.6 °C (summer). The concentration of UN in the urine and the TAN concentration in the slurry top layer (laboratory analysis) increased with the RDP content. Furthermore, the maize-based diets resulted in greater UN and TAN concentrations. The pH of the urine and the top layer of the slurry were measured in samples taken on the spot.

Data on the number of animals, the urea nitrogen concentration and the TAN concentration of the top layer of the slurry (TAN_{top}) were used as direct input for the model. The temperature of the floor and the top layer of the slurry were assumed to be the same as the mean temperature inside the house.

Based upon the work presented in Chapter 4, the floor pH was equal to the urine pH plus 1.0 pH unit. Similarly, the pH of the slurry in the pit was related to the urine pH. A factor of 0.2 was added to the urine pH instead of 0.5. This adaptation was found to compensate for the omission of the NH_3 concentration of the pit air in the slurry pit module of the 1998-model. Furthermore, urination frequencies were estimated at 9, 10 and 11 per animal per day for the M, GM and G treatments, respectively (Smits, personal communication).

Table 7.2: Overview of data collected during the last week of each of the 13 three week periods where cows were fed different diets in a naturally ventilated cubicle house in Lelystad (diet components: G = grass; GM = grass and maize; M = maize).

	Diet code (component and RDP content; g per day per animal)												
	G0	G500	G500	G1000	G1000	GM0	GM0	GM500	GM1000	M0	M0	M500	M1000
Number of Animals	57	55	57	57	57	55	57	57	56	57	57	56	56
Mean inside temperature (°C)	8.8	16.4	4.9	21.6	4.9	16.4	15.2	14.4	11.5	17.9	8.8	4.3	14.1
Urea N (UN; g L^{-1})	3.0	3.5	3.8	5.0	5.0	3.4	3.6	5.2	7.1	4.4	6.9	9.8	11.9
TAN_{top} (g L^{-1})	1.30	1.40	1.49	1.94	1.83	1.19	1.16	1.50	2.05	1.66	1.37	2.51	1.88
TAN:UN ratio (-)	0.33	0.40	0.39	0.39	0.37	0.35	0.32	0.29	0.29	0.38	0.20	0.26	0.16
Urine pH (-)	8.1	8.4	8.5	8.5	8.4	8.3	7.9	8.7	8.6	8.1	8.4	8.3	8.6
Slurry top pH (-)	7.6	7.8	7.8	7.8	7.9	7.5	7.3	7.6	7.8	7.6	7.7	8.2	7.9

The measurement period with the least measured NH_3 emission (G0) was used to calibrate the model. As a consequence, the following additional parameter values were used for the simulation of all periods:

- v_{floor} = 0.1 m s^{-1}
- v_{pit} = 0.05 m s^{-1}
- A_{pit} = 207 m^2

The smaller surface area of the pit when compared to the total pit area is assumed to realistically reflect the part of the surface area that contributes to the emission from the pit. The air volume beneath the cubicles is more or less a confined space and will consequently contribute less to the pit emission (see Chapter 6).

3.4 Results and Discussion

The comparison of simulations for all treatments with the mean measured emission is presented in Figure 7.6.

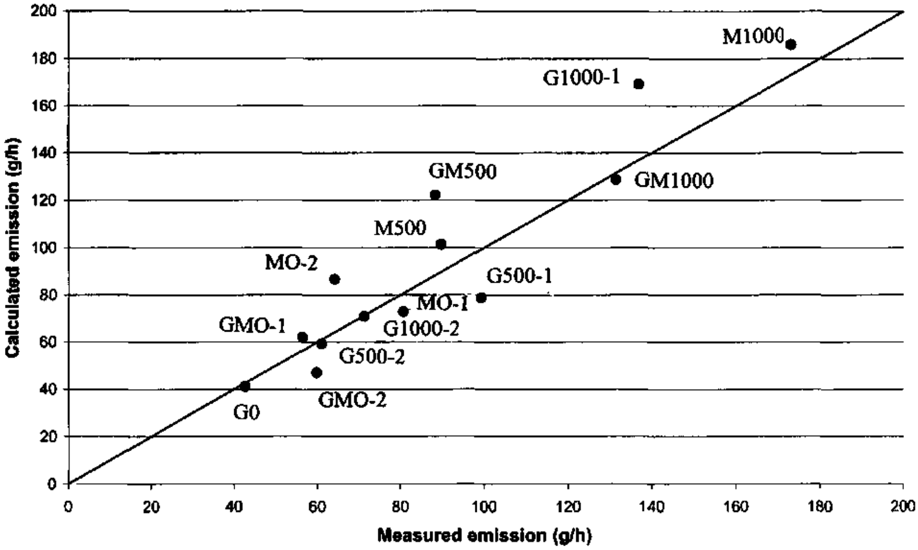

Figure 7.6: Measured versus calculated ammonia emission for 13 treatments with dairy cow diets with different composition and rumen degradable protein content, conducted in the Lelystad cow house.

Calculated and measured NH_3 emissions matched satisfactorily. The model was able to simulate well the effect of differences diet related parameters (UN and TAN concentrations) and temperature on the NH_3 emission from the house. Combining Table 7.2 and Figure 7.6 shows that the NH_3 emission increases with the urea concentration in the urine. The maize based diets resulted in much greater urea concentrations than the GM and G diets. This was caused by the lesser urine production for the maize based diets (Bannink *et al.*, 1999). Moreover, the temperature played an important role, as demonstrated by the difference in NH_3 emission between the G1000 and G500 treatments.

The results indicate that the model reliably simulates the emission levels for different dairy cow diets when detailed information is available on the indoor air temperature, and the composition of the urine produced (pH, concentration of urinary nitrogen) and the slurry top layer (pH, total ammoniacal nitrogen concentration). This means that the model is capable of predicting the emission reduction by feeding strategies when the indicated data are present. Moreover, animal nutritionists now have a tool to design and evaluate dairy cow diets that reduce NH_3 emissions.

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8

General Discussion

1 Introduction

Central theme of this thesis is the development of a mechanistic simulation model for the NH_3 emission from dairy cow houses. The model presented in the previous chapters describes the fundamental processes of NH_3 production and volatilization from urine and the slurry pit. It has especially been developed for cubicle dairy cow houses because:

- the vast majority of dairy cows in the Netherlands and other countries with intensive dairy production is kept in cubicle houses;
- a drastic reduction of the NH_3 emission from animal houses is needed to comply with environmental protection policies on NH_3 deposition;
- dairy cow houses are a large single source of NH_3 emission, in the Netherlands being in the same order of magnitude than slurry application (LME, 1999), and can, therefore, largely contribute to the required emission reduction.

The goals associated with the model development follow from the intended use of the model for legislation, research, and farmers' advisory, and to result in or support:

1) production and assessment of data on NH_3 emission levels (emission factors) for the common dairy cow houses;
2) development of dairy cow housing systems with low NH_3 emission as a contribution to cattle farming systems with optimal nutrient management;
3) evaluation of NH_3 emissions from dairy cow houses in current and innovative dairy farming systems
4) quantification of realistic NH_3 emission fractions for use in regional and national emission inventories and studies.

2 The goals reviewed

2.1 Production and assessment of NH_3 emission data for dairy cow houses

The strength of the model for production and assessment of data on NH_3 emission levels for cubicle dairy cow houses was illustrated throughout this thesis. This aspect was emphasized in Chapters 3 and 6 (experiments in a mechanically ventilated cubicle house in Duiven), and Chapter 7 (data sources from the naturally ventilated cubicle house in Wangen-Leupolz). The results presented in Chapter 6 demonstrated that a full set of measured input data assures an accurate simulation of measured NH_3 concentrations in the air in the slurry pit and NH_3 emissions from the house. Fewer measured input data were found to also result in adequate simulation results, expressed as monthly mean emission levels (Chapter 3) and as continuous emission curves (Chapter 7). Model calculations can now replace emission measurements, with the consequence that more NH_3 emission data can be produced against lesser costs. The model is particularly sensitive to three key variables: pH, urea N concentration in the urine, and temperature (Chapter 3). Their values need to be known at least to adequately run the model, as is elaborated below.

pH

The work presented in Chapter 4 has provided new and essential information on the development of the pH of urine deposited on slatted floors and on slurry in the pit. The constant pH value of 8.6, used in previous studies and models (e.g. Elzing and Monteny, 1997; the 1998-model presented in Chapter 3), was found be unrealistic. The urine pH appeared to increase exponentially with time. Moreover, the pH of urine on the slatted floor increased to much greater values. These maximum values were reached within 10 h after urine deposition. The increase of pH, relative to the pH of the fresh urine, was:

- 1.0 pH unit for a clean or scraped slatted floors (Equation 6.6; Table 4.4);
- 0.5 pH unit for the top layer of the slurry in the pit (Equation 6.3, Table 4.4).

These findings implicate that the – hard to measure – pH of urine deposited on the floor and on the top layer of the slurry pit can now be replaced by the – more easy to measure – pH of the urine produced by the cows.

Equation 6.3 was found to be equal to the pH of the slurry top layer plus 1.3 pH units (Chapter 4). Furthermore, adapted equations were derived for urine deposited on faeces, resulting in an increase of 1.4 pH units relative to the pH of the faeces. Equation 6.3 is used in the NH_3 mass balance of the slurry pit air. An adapted value of 0.2 pH unit instead of 0.5 was suggested when the 1998-model is used, with the total ammoniacal nitrogen mass balance for the slurry in the pit. This assumption compensates for the lack of inhibition of the volatilization by the NH_3 concentration in the slurry pit module of the 1998-model. The validity of this assumption follows from a comparison of simulations with the 1998-model and the extended model presented in Chapter 6 with the measured emission levels using the equations indicated above.

As can be concluded from the previous section, pH is a complex aspect. Aside from this complexity, small errors in the pH measurement have great effect on the simulation results. This is illustrated by the data presented in Table 8.1, calculated with Equation 3.5. The fraction of unionized NH_3 in the liquid triples per 0.5 pH unit at all temperatures. Because of this, an accurate pH measurement, preferably conducted in-situ, is essential for a correct prediction of the NH_3 emission from the pit and the floor.

Table 8.1: Values for the fraction of unionized ammonia (% of total ammoniacal nitrogen) as a function of pH and temperature, calculated with Equation 3.5.

	Temperature (°C)				
pH (-)	0	5	10	15	20
7.5	0.07	0.1	0.13	0.18	0.26
8.0	0.21	0.29	0.41	0.57	0.80
8.5	0.66	0.92	1.3	1.8	2.5
9.0	2.1	2.9	4.0	5.5	7.5
9.5	6.2	8.5	11.0	15.4	20.0

Nitrogen concentration in the urine

As shown in Chapters 2 and 3, the NH_3 emission increases linearly with the concentration of urea nitrogen in the urine. This parameter can be determined in samples taken from the urine as it is produced. Because of the drawbacks of urine sampling under practical conditions, other options to obtain input data on the urea nitrogen concentration are through:

(1) cattle nutrition models;

(2) sampling and analysis of the top layer of the slurry in the pit.

The first option can be realized with a combination of the mechanistic model presented by Van Straalen (1995) simulating nitrogen fluxes excreted with urine and faeces (and milk), and the empirical model for urine volume predictions described by Bannink *et al.* (1999).

The method behind the second option was presented in Chapter 3 (Equation 3.11), for the frequently mixed content of the slurry pit in the Duiven cow house, and applied in Chapter 7 for the Lelystad cow house. The concentration of total ammoniacal nitrogen of the slurry is used to estimate the concentration of urinary nitrogen, assuming constant volumes of faeces and urine produced. For most dairy cow diets tested in that cow house, the ratio between the concentrations of total ammoniacal nitrogen and urinary nitrogen were between 0.3 and 0.4 (Table 7.4). The option of slurry sampling and total ammoniacal nitrogen analysis seems the most practical solution, although this ratio may vary between individual farms.

Temperature

Temperature is an important input parameter, because it is a key variable in most of the fundamental biological and chemical processes involved (Chapters 2 and 3). Moreover, the difference in temperature of the outside air and the air in the pit determines the air exchange rate through the slatted floor and thus influences the NH_3 emission from the pit (Chapters 5 and 6). The experiments presented in Chapter 5 provide a solid basis for modeling of the air exchange rate through the openings of the slatted floor. The importance of the contribution of the slurry pit to the total NH_3 emissions from the house was clearly demonstrated in Chapter 6, and quantification of the NH_3 emission from the pit is now possible. As was discussed in Chapters 6 and 7, the model overestimates the air exchange rate through the floor openings and thus the NH_3 emission from the pit at small and negative temperature differences (stagnant pit air). Moreover, air exchange through the slatted floor can be hindered by the presence of faeces on the slatted floor. Suggestions for an adapted equation for clean and faeces covered slatted floors were presented in Chapter 6 and 7, respectively. However, further research may be needed to refine the model for different floor systems and geometry.

2.2 Development of low NH_3 emission housing systems for dairy cows

Dairy cow housing systems with a reduced NH_3 emission have to be developed and implemented in the next years in the framework of the Dutch legislation on NH_3 emission abatement from agriculture. The so-called Green Label Awards were introduced during the last decade of the past century to stimulate the investment in these housing systems on a voluntary basis. Green Label houses have to reduce the NH_3 emission by at least 50% compared to traditional housing, without causing a shift towards other sources of environmental pollution (e.g. increased use of fossil energy, emission of greenhouse gases, odor emission)..An overview of the dairy cow housing systems that potentially comply with the Green Label requirements is presented in Chapter 2. In practice, however, few of these systems are being constructed. Only cubicle houses with adapted floor design (e.g. grooved floors; Swierstra and Braam, 1999) are being built in relatively large numbers. Main reasons for this are the high costs associated with renovation and construction of the housing systems. Additional legislation is currently being prepared, with the ALARA-principle (As Low As Reasonably Achievable) as a basis. Practical implications of this will be that technological solutions with a lesser reduction percentage can be allowed. Also, other emission reducing measures like animal nutrition and the use of slurry additives can be found to comply with ALARA too. The results of the simulation of the NH_3 emission levels for different dairy cow diets (Chapter 7) illustrate the great potential of feeding measures for dairy cows as a means to reduce NH_3 emissions. The model predicted the emission levels well with the available set of input data. It can replace the complex and costly emission measurements in nutrition experiments conducted in a well-defined facility.

The potential of the model to support the development of low emission housing systems for dairy cows is also related to the possibilities for separate simulation of the NH_3 emission from the floor and the slurry pit. A unique tool for this purpose is now available with the NH_3 emission model presented in Chapter 6. It can be used for the development of reduction measures that specifically act on the pit or the floor, for the prediction of the emission reduction associated, and for the explanation of emission reductions reported in previous experiments (see e.g. Chapter 2). As an example, the work presented in Chapter 5 indicated that a smaller temperature difference between the air in the pit and the outside air results in a reduction of the air exchange through the slatted floor and consequently the NH_3 emission from the slurry pit. The theory developed and applied in the model can now be used to quantify the NH_3 emission reduction from innovative climate control systems for dairy cow houses that result in heating of the outside air before (e.g. with a heat exchanger) or upon (e.g. by conducting the incoming air to improve mixing with air inside the house) entering the house. This type of system design was not further investigated in this thesis.

2.3 Evaluate NH_3 emissions from cow houses in current and innovative farming systems

As stated before, the model can potentially replace NH_3 emission measurements. This is also valid for field studies. In the on-going project "Koeien en Kansen" (Cows and Chances), a group of 17 dairy farmers is encouraged to optimize their nutrient management with the aim to reach legislatively enforced limits on nutrient losses over the next years. A monitoring program is set up to quantify nutrient losses before, during and after the transition from traditional to optimal nutrient management. The model presented in this thesis is used for prediction of the NH_3 emission from the cow houses and is embedded in a whole-farm NH_3 emission model (Smits *et al.*, 1998), but this is not included in this thesis.

Optimal nutrient management is also considered the most important challenge for dairy farmers to meet sustainability criteria related to ground and surface water pollution from nitrogen and phosphorus. Aarts (2000) demonstrated that the N and P surplus and thus the losses on dairy farms can be reduced drastically at reasonable costs. His prognoses for the innovative dairy farm "De Marke" are that N and P efficiencies (output/input) will be 36% and 100% in the future, whereas this is 16% and 27%, respectively, on average dairy farms today. For N, this partly can be achieved by a combination of increased valuing and use of the nutrients in the animal excreta as a fertilizer, optimal feeding strategies, livestock management, and minimization of the input through chemical fertilizers and concentrates. Additionally, measures are being taken to minimize losses of NH_3 from the house (through innovative floor systems), the outdoor slurry storage (by covering), slurry application (using sod injection techniques) and grazing (through part time grazing). This illustrates a number of changes in dairy farming needed to comply with sustainability criteria. Detailed knowledge of the complete chain of nutrient related processes on the farm level is necessary to support the development of such innovative farming systems. An integrated farm system model is an important tool in this framework. Such a model should not only be able to support the development of farming strategies aiming at an increase in the ratio between output and input of nutrients, but also to support the implementation of measures that reduce the loss of nutrients to all environmental compartments (soil, water, air). Focussing on NH_3, a form of N loss that only occurs to the air, strategies should reflect on all phases of the farming process (house, outdoor storage, land application of excreta, grazing) in an integrated way.

2.4 Quantification of Emission fractions for regional and national emission inventories

Emission fractions (e.g. NH_3 emission from the cow house expressed as a percentage of the N excreted by the cows; see Chapter 1) are commonly used in emission inventory studies (Leneman *et al.*, 1998; Van der Hoek, 2000). They are an essential element of the equations in national, regional and farm-scale emission or nutrient models. Currently, fixed emission fractions are available (see Chapter 1) for the most common types of dairy cow houses (cubicle houses, tying stalls). The work presented in this thesis has clearly shown that the NH_3 emission from dairy cow houses varies with factors that are related to the house design, the indoor climate, the cows' diet, and the farm management. Moreover, the knowledge on processes and variable parameters included in the model offers a basis for specification of current emission fractions for dairy cow houses. Data presented in Chapters 3 (Duiven) and 7 (Lelystad) illustrate this. Ammonia emissions for the Duiven cow house (Table 3.2; fixed diet) and the cow house in Lelystad (Figure 7.6; variable diets) can be related to the amount of N excreted with urine and faeces. The amount of N excreted is calculated as the difference between N intake and N excreted with milk, being an approximation of the N excretion (Smits, personal communication). The results are summarized in Table 8.2.

The data in Table 8.2 demonstrate that the emission fraction increases with temperature (Duiven data; one grass and maize based diet), which is related to the temperature dependency of the NH_3 emission. The Lelystad data illustrate the temperature dependency (G1000 and M0 replicates) and the relationship between the emission fraction and the diet composition. Both factors result in an emission fraction ranging between 4.6% and 11.8%. The current fixed emission fraction for cubicle dairy cow houses used in national emission inventories (14.7%, recently revised to 10.2%: Steenvoorden *et al.*, 1999; Van der Hoek, 2000) can now be further revised. The NH_3 emission model is also a powerful instrument to generate differentiated emission fractions for use in emission inventories on a smaller scale. It includes variable parameters that reflect differences in local and regional situations (e.g. geometry aspects of housing systems, grazing strategies, composition of the roughage component in the diet) and in seasonal aspects (e.g. climatic conditions). This opens possibilities for a more realistic inventory of NH_3 emissions from dairy cow houses on a local and a regional scale, including the temporal variation in emissions. For example: a change of 1% in the emission fraction for cattle houses represents an NH_3-N emission of 0.613 kg per animal for the housing period (see Chapter 1). For the total herd of cattle in the Netherlands (4.2 million head; LME, 1999), this would mean a change in the NH_3-N emission of around 2.6 million kg, being approximately 1.5% of the national NH_3-N emission today.

Table 8.2: Overview of the calculated nitrogen excretion with urine and faeces (g N per animal per day) and ammonia emission (measured in g N per animal per day and calculated as % of N excreted) for the mechanically ventilated dairy cow house in Duiven and for the naturally ventilated dairy cow house in Lelystad. For the Lelystad cow house, the diet codes are the same as in Table 7.2.

	N excretion (Nintake – Nmilk)	Mean N emission	Mean temperature (°C)	Emission fraction
Duiven (month)				
January	352	25.6	11.8	7.4
February	352	28.4	12.4	8.1
March	352	29.1	14.4	8.3
April	352	30.1	14.1	8.8
May	352	39.9	18.4	11.3
Lelystad (diet code)				
G0	323	14.8	8.8	4.6
G500-1	335	34.4	16.4	10.3
G500-2	383	21.2	4.9	5.5
G1000-1	444	47.4	21.6	10.7
G1000-2	381	24.7	4.9	6.5
GM0-1	351	19.6	16.4	5.6
GM0-2	326	20.7	15.2	6.3
GM500	401	30.6	14.4	7.6
GM1000	497	45.6	11.5	9.2
M0-1	342	28.0	17.9	8.2
M0-2	369	22.2	8.8	6.0
M500	494	31.1	4.3	6.3
M1000	507	60.0	14.1	11.8

3 Conclusions

1. A simulation model for ammonia emissions from dairy cow houses is now available. It is validated against emission measurements on various locations in and outside the Netherlands, and is now ready for use as a tool for legislation, research and advisor purposes.

2. The model has two basic versions: (a) the production model, with nitrogen mass balances for the top layer of the slurry and for each urine pool deposited on the floor, and (b) the emission model, consisting of mass balances for the pit air and the air above the floor. Both versions describe the same basic processes: urination behavior, urea conversion, dissociation and volatilization. The production model can be used under stationary conditions, whereas the emission model is capable of dynamic simulation.

3. The model is the most sensitive to the pH of the urine deposited on the floor and on the slurry in the pit. To run the model, accurate values of this variable parameter are needed. Equations for the pH of the floor and the top layer of the slurry in the pit are derived from experiments and improve the validity of the model and the quality of the simulations.

4. The experimental work on the air exchange rate through the slatted floor added an important feature to the model, namely the ability to separately quantify the ammonia emission from the pit and the urine on the floor. Consequently, the development of separate or combined measures for emission reduction from the pit and the floor is now possible.

5. The slurry pit contributes on average for 25-40% to the ammonia emission from cubicle dairy cow houses with slatted floors, with a maximum percentage up to 80 in situations with great differences in temperature between outside air and air in the slurry pit.

6. The ammonia emission from the house can be reduced substantially by changing the cows' diet.

7. The potential of the model to support the selection of measures that reduce the NH_3 emission from dairy cow houses was illustrated for the diet of the cows. Animal nutritionists now have a powerful tool to develop and evaluate feeding measures that reduce NH_3 emissions from dairy cow houses.

8. The model can be used to calculate emission fractions for use in emission inventories on farm, local and national scales.

9. Using the model to support the development and evaluation of new farming systems with improved nutrient management is potentially possible.

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Summary

There is general consensus that the emission of ammonia has to be reduced to protect natural ecosystems. Cattle husbandry is the largest single source of ammonia emission. Emission reduction measures are relevant for the cow house, the outside slurry storage, land application of slurry, and grazing. A mechanistic model for the ammonia emission from dairy cow houses was developed and validated to facilitate and support:

- production and assessment of ammonia emission data for legislative purposes
- development of low emission cow housing systems
- evaluation of ammonia emissions from houses in farming systems
- quantification of emission fractions for regional and national emission inventories

Ammonia in dairy cow houses originates from urea excreted with urine. Temperature, air velocity and pH are the most important variable parameters of the volatilization process. They determine, together with system related parameters like surface area of the floor and the slurry pit, the emission levels for different housing systems for dairy cows. Moreover, measures that reduce the ammonia emission from cow houses influence one or more of the parameters.

The model presented in this thesis has been developed from a version with the ammoniacal nitrogen mass balance for the urine pools on the floor and the slurry in the pit to a version with ammonia mass balances for the air in the pit and the air above the floor. In-depth experiments have been conducted to fill in gaps in knowledge about:

- the development of the pH of urine deposited on floors and on slurry (laboratory experiments and one in-situ measurement)
- air exchange rates through slatted floors (laboratory and full scale research)

Laboratory experiments and measurements in a dairy cow house revealed that the pH of urine deposited on concrete floors and on slurry develops exponentially towards a constant level. The pH of urine on floors increased with 1 pH unit within 10 hours from the pH of the excreted urine. This increase was 0.5 pH unit for urine deposited on slurry. These findings are markedly different from the constant values of the pH used in previous models. They are explained from the volatilization processes of ammonia and carbon dioxide, produced from urea.

The air exchange through slatted floors for dairy cow houses has been studied in a laboratory experiment for situations with forced convection and thermal buoyancy. Measurements in a full scale dairy cow house, using carbon monoxide as a trace gas, resulted in unique equations for the air exchange rate through openings in the slatted floor as a function of differences in temperature between outside air and air in the pit. The results are in accordance with the findings from the laboratory research. The air exchange rate increased linearly with the temperature difference and is affected by the ventilation rate of the cow house.

An extended model has been developed, using the results from the experimental work on pH development and air exchange rate. This has resulted in a model that describes the ammonia mass balance for the slurry pit air and for the air above the floor. Simulated ammonia emissions from the house and ammonia concentrations in the pit air appeared to match measured values well for three independent periods distributed over one year. The pH of the top layer of the slurry pit and the air exchange rate through the slatted floor at small and negative temperature differences (stagnant pit air conditions) were adapted to some extent. The slurry pit appeared to contribute for on average 25-40% to the total ammonia emission from the house, with a maximum percentage of 80 in situations with relatively cold outside air.

The model has been used for simulation of ammonia emissions a commercially operated, naturally ventilated cubicle house for dairy cows in Wangen-Leupolz (southern Germany) and for simulation of ammonia emissions from dairy cows fed with nine different diets in a naturally ventilated cubicle house for dairy cows at the experimental farm 'De Waiboerhoeve' in the Netherlands. The model has reliably simulated ammonia emissions in both cases, using a part of the measurement periods for calibration. Moreover, the ammonia emission from the farm at the experimental farm was drastically reduced through diet manipulation, which could be simulated with the model using on site parameters. Dairy cow nutrition research now has a powerful tool to develop and assess diets that reduce ammonia emissions.

The fixed emission fractions for dairy cow houses, representing ammonia emission as a percentage of the nitrogen excreted in the house, used in regional and national emission inventory studies can now be further refined. The research conducted in the framework of this thesis offers a basis for the quantification of emission fractions that take time and location specific parameters into account.

Samenvatting

Er is algemene consensus dat de emissie van ammoniak moet worden teruggedrongen om natuurlijke ecosystemen te beschermen. De rundveehouderij is de grootste bron van ammoniakemissie. Emissiebeperkende maatregelen kunnen betrekking hebben op de stal, de buitenopslag, mesttoediening en beweiding.

Een mechanistisch simulatiemodel voor de ammoniakemissie van melkveestallen was ontwikkeld en gevalideerd, teneinde:

- emissiedata beschikbaar te krijgen voor wettelijke doelen
- de ontwikkeling van emissie-arme huisvestingssystemen te ondersteunen
- ammoniakemissies op het niveau van het rundveehouderijssyteem te evalueren
- emissie-fracties te generen voor gebruik in regionale en nationale emissiestudies

Ammoniak in rundveestallen is afkomstig van ureum dat wordt uitgescheiden met de urine. Temperatuur, luchtsnelheid en pH zijn de belangrijkste variabelen in het emissieproces. Ze bepalen, samen met systeemgerelateerde parameters zoals de oppervlakten van vloer en mestkelder, het emissieniveau voor de verschillende huisvestingssystemen voor rundvee. Daarnaast grijpen emissiebeperkende technieken in op één of meerdere van die variabelen of parameters.

Het model dat in dit proefschrift centraal staat werd ontwikkeld van een versie met de ammoniak-massabalans voor de urineplassen op de vloer en de mest in de kelder tot een versie met de ammoniak-massabalans voor de kelderlucht en de stallucht. Verdiepende experimenten werden uitgevoerd om de belangrijkste ontbrekende kennis in te vullen, n.l.:

- de ontwikkeling van de pH van urine op de stalvloer en op de mest in de kelder (laboratoriumexperimenten en een *in-situ* meting)
- luchtuitwisseling door de roostervloer (laboratoriumexperimenten en onderzoek op praktijkniveau)

Uit de eerst genoemde laboratoriumexperimenten en de praktijkmeting bleek dat de pH van de urine vanaf het moment dat de urine wordt gedeponeerd exponentieel toeneemt tot een constante waarde. Voor de urine op de stalvloer was deze toename 1 pH-eenheid binnen een tijdsbestek van 10 uur. De pH van de urine op mest in de kelder nam met 0,5 pH-eenheid toe. Deze uitkomsten verschilden aanmerkelijk van de pH-waarden die tot dan toe in emissiemodellen werden aangenomen. De bevindingen konden worden verklaard uit de emissie van ammoniak en kooldioxide, afkomstig van de omzetting van ureum.

De luchtuitwisseling door de openingen in een roostervloer werd onder laboratoriumomstandigheden bestudeerd, waarbij onderscheid werd gemaakt tussen situaties met gedwongen en vrije convectie. De metingen op praktijkniveau, waarbij gebruik werd gemaakt van koolmonoxide als tracergas, resulteerde in unieke formules voor de luchtuitwisseling door roosters als een functie van verschillen in temperatuur tussen buitenlucht en lucht in de kelder. De resultaten, die in het verlengde lagen van de uitkomsten van het laboratoriumonderzoek, toonden een lineair verband tussen de luchtuitwisseling en het temperatuursverschil, terwijl ook het ventilatiedebiet van de stal effect had.

Het simulatiemodel, uitgebreid met de bovengenoemde bevindingen, beschrijft de ammoniak-massabalansen voor de kelderlucht en de stallucht. Uit een validatiestudie bleek dat de ammoniakconcentratie in de kelderlucht en de ammoniakemissie van de stal goed overeenkwamen met de gemeten waarden, wanneer de ontwikkelde theorie rond pH en luchtuitwisseling werd betrokken op de lokale situatie en de actuele omstandigheden.

De mestkelder bleek gemiddeld voor 25-40% bij te dragen aan de emissie vanuit de stal, waarbij de bijdrage soms kon oplopen tot 80%, vooral in situaties met relatief koude buitenlucht.

Het model werd gebruikt voor de simulatie van de ammoniakemissies van een natuurlijk geventileerde ligboxenstal in Wangen-Leupolz (Zuid-Duitsland) en van een natuurlijk geventileerde ligboxenstal voor melkvee van het proefbedrijf "De Waiboerhoeve" in Lelystad waar veevoedingsonderzoek met negen verschillende rantsoenen werd uitgevoerd. In beide gevallen konden de gemeten ammoniakemissies goed worden gesimuleerd, wanneer een deel van de meetperiode werd gebruikt voor modelkalibratie. Uit de simulaties voor de stal in Lelystad bleek daarnaast dat de ammoniakemissie uit melkveestallen drastisch kan worden beperkt door rantsoenaanpassingen. Het model was in staat om dit te simuleren. Dit betekent dat het veevoedingsonderzoek nu een krachtig instrument beschikbaar heeft om vooraf de emissiebeperkende potentie van rantsoenen te bestuderen.

Vaste emissie fracties voor melkveestallen, waarmee de ammoniakemissie wordt uitgedrukt als percentage van de uitgescheiden hoeveelheid stikstof, worden in het algemeen gebruikt in emissie-inventarisaties. Het onderzoek heeft uitgewezen dat de tot nu toe gebruikte vaste waarde per stalsysteem kunnen worden verfijnd, zowel in de tijd als naar locatie, gebruik makend van de kennis van tijd- en locatiegebonden variabelen.

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Toen ik in mei 1991 bij het IMAG (toen nog IMAG-DLO en Instituut voor Mechanisatie, Arbeid en Gebouwen, thans instituut voor Milieu- en Agritechniek) kwam werken, hadden Aad Jongebreur, Jos Metz en ik al afspraken gemaakt over promoveren. Het duurde tot februari 1994 voordat Aad me bij hem riep en me meedeelde dat het nu toch wel hoog tijd werd om een serieuze start met het onderzoek te maken. Al met al heeft het dus ruim 6 jaar geduurd voordat dit werk werd afgerond. Het feit dat ik het 'erbij' moest doen, is nauwelijks een excuus voor deze toch wel lange tijd. Of misschien ook wel. Je moet je tijd en aandacht verbrokkelen en kunt niet aan een stuk doorwerken. Op het laatst heb ik dat wel gedaan en kon ik gelukkig snel tot een afronding komen. Tenslotte moet ik toegeven (en iedereen die me kent, weet dat van mij) dat ik mijn prioriteit altijd bij mijn gezin leg en 's avonds ook niet altijd de puf heb gehad om – na een dag intensief werken – nog eens achter de PC te kruipen voor een paar bladzijden tekst.

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Curriculum Vitae

Gerrit Jan Monteny was born on 15 July 1960 in Rotterdam. He grew up on a mixed farm (cattle and arable land) in Zwartewaal (Z-H). In 1978 he completed the secondary school (VWO) at the Blaise Pascal in Spijkenisse and started in the same year his studies in Agricultural Engineering at Wageningen University (WU). His MSc. projects concerned: (1) the development and *in-situ* testing of a simulation model for the ammonia emission from broiler houses, and (2) the development and introduction in practice of a module to calculate financial aspects of investments on dairy farms, as a part of the Dairy Farm Budget Programme (BBPR). Practical training programmes were a part of these projects and were spent at the "Gezondheidsdienst voor Dieren" in Boxtel (NL) and at the Research Station for Cattle, Sheep and Horse Husbandry in Lelystad (NL). He received his MSc. degree in June 1987.

His career started half a year before he left WU, as assistant co-ordinator of the national research programme on manure and ammonia. This job resorted under the former Directorate for Agricultural Research (DLO). In 1991 he started at the Institute of Agricultural and Environmental Engineering (IMAG) as head of the Department of Manure Handling and Emissions. He now is head of the research cluster "Emissions and Indoor Climate".

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